EEIST

THE NEW ECONOMICS OF INNOVATION AND TRANSITION: EVALUATING OPPORTUNITIES AND RISKS

A REPORT BY THE ECONOMICS OF ENERGY INNOVATION AND SYSTEM TRANSITION (EEIST) CONSORTIUM

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EEIST

About

The Economics of Energy Innovation and System Transition (EEIST) project develops cutting-edge energy innovation analysis to support government decision making around low-carbon innovation and technological change.

By engaging with policymakers and stakeholders in Brazil, China, India, the UK and the EU, the project aims to contribute to the economic development of emerging nations and support sustainable development globally.

Led by the University of Exeter, EEIST brings together an international team of world-leading research institutions across Brazil, China, India, the UK and the EU.

The consortium of institutions are **UK:** University of Exeter, University of Oxford, University of Cambridge, University College London, Anglia Ruskin University, Cambridge Econometrics, Climate Strategies, **India:** The Energy and Resources Institute, World Resources Institute, **China:** Tsinghua University, Energy Research Institute, **Brazil:** Federal University of Rio de Janeiro, University of Brasilia, Universidade Estadual de Campinas (UNICAMP) **EU:** Scuola Superiore di Studi Universitari e di Perfezionamento Sant'Anna.

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Foreword

When the UK first supported the deployment of offshore wind, it generated electricity at around three times the market price. Few people guessed that within a decade, costs would fall by 70 per cent, allowing offshore wind to provide electricity at less than the market price.

Just six years ago, we aimed to deploy 20 GW of offshore wind in the UK by 2030. With the announcement last year of the Prime Minister's Ten Point Plan for a Green Industrial Revolution, we doubled that target to 40 GW by 2030 – enough to power every home in the country. Meanwhile, the number of high-quality jobs supported by the industry and its supply chains continues to grow.

It is not only in the UK that progress in clean technologies has been faster than expected. The amount of solar power deployed globally in 2020 was over ten times higher than experts had forecast only fifteen years before. Similarly, analysts' predictions of the share of electric vehicles in global car sales continue to be revised radically upward. As we aim to keep the goals of the Paris Agreement within reach, and to maximise the benefits of the transition to net zero emissions, it is crucial that we learn the lessons of these successes.

Last year, the UK Government issued new guidance on policy appraisal in contexts of transformational change. This recognised that when the future is uncertain, the aim of analysis is less to predict outcomes precisely, and more to find the points of leverage – places where a small intervention can have a large effect. I am delighted that researchers from the UK, China, India and Brazil are working together to deepen our understanding of where such leverage points for transformational change can be found, and to apply this to addressing climate change and ecosystem degradation, our greatest shared challenge.

The International Energy Agency has estimated that without international collaboration, the transition to net zero global emissions could be delayed by decades. On the other hand, if we work together, we can innovate faster, realise larger economies of scale, and create stronger incentives for investment. As countries of the world come together at COP26, we must be guided by this positive vision. With determined action and sustained collaboration, we can create new economic opportunities while securing a safe climate for the future.

Nick Bridge
Foreign Secretary's Special Representative for Climate Change
Foreign, Commonwealth & Development Office

Preface

Energy is at the heart of human development, but also of what is now one of humanity's most pressing problems – climate change.

Economics has traditionally seen the challenge as one of managing difficult trade-offs between the pursuit of economic growth and the cost of cutting GHG emissions. On the surface, it seems that emissions reduction has consistently lost out to the pursuit of economic objectives, with global emissions continuing to rise.

The reality is more interesting and more hopeful, and it more fundamentally suggests the need to revise our basic economic perspective. Along with rising climate impacts, the last decade has seen radical developments in low-carbon technologies once assumed to be very costly and/or too limited. Such developments not only open the door to reducing global emissions relatively cheaply, they challenge the use of traditional economic appraisals when we pursue goals of transformational change. For example:

- Wind energy was once characterised as inefficient, limited and expensive – particularly offshore wind. But in the space of barely a decade it has become established as an important and cost-effective source – increasing from under 1%, to 10–15% of electricity supplies in Brazil and the EU respectively, for example, and with offshore wind now forming the largest single element of the UK's electricity and decarbonisation strategy.
- As recently as 2014, *The Economist* described solar PV as "the most expensive way to reduce carbon emissions".[1] Only six years later, the IEA acknowledged it as offering "the cheapest electricity in history", growing exponentially, with the focus having shifted rapidly from the rich world to China, and now on to offering a key development tool for providing cheap energy to some of the poorest people on the planet.
- Throughout the last century, most of the world's lighting was still provided by heating wires in bulbs, wasting extraordinary amounts of energy. Today, such bulbs are mostly abandoned, and even banned in some regions because the alternatives are so much better and cheaper. Alongside its general electrification programme, efficient lighting policy in India resulted in annual sales of the most efficient lighting – LED bulbs – soaring from just 3m in 2012 to 670m in 2018. Prices fell by 85%, cutting energy bills and emissions, and – as with PV – moving the technology from being the most expensive to the cheapest on offer.

This report is not only about the promise such technologies hold for the clean energy transition, but about the lessons we can draw from such examples. It is about how we think, and often fail to recognise or understand the opportunities that arise from innovation and transition in major technologies and systems. Case studies, detailed in the Online Appendix, delve further into the three cases illustrated above, including their development in the major emerging economies indicated. Beyond R&D, all highlight strong and sustained government action in market and industry developments. Moreover, often it was action taken despite (rather than because of) traditional approaches to economic appraisal – delivering changes which have rendered largely irrelevant numerous historical (and even recent) modelling estimates of how much it would cost to tackle climate change – and how best to go about it.

Consequently, this report starts by outlining the fundamental features of traditional economic appraisal. It then turns to look at each of the three historical cases above, including how these changes occurred and the role of government policy and appraisal in each.

The report then outlines alternative approaches to economic appraisal which better capture the real economics of innovation and transition, particularly in relation to the challenge of deep decarbonisation. We then consider the implications for two more transitions to technology currently at earlier stages of emergence, namely:

- Road transport, which accounts for around 15% of global emissions. Electric vehicles which, though they currently account for under 1% of road travel globally, have recently been growing at a rate of 40% per year.
- Steelmaking technologies, which account for over 5% of global emissions and have traditionally been classed as one of the hardest-to-treat sectors, but in which there is now much activity.

We then draw conclusions, not only about the prospects for decarbonisation, but about the analytic and modelling tools needed to help governments, in particular, navigate one of the greatest and most important, set of economic transitions since the Industrial Revolution – the road to net zero.

Michael Grubb
17 October 2021

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Acronyms

R&D – Research and development
CBA – Cost-benefit analysis
ROA – Risk-opportunity analysis
EV – Electric vehicles
RO – Renewables obligation
CfD – Contract for difference
FiT – Feed in tariff
ETS – Emissions trading scheme
LED – Light-emitting diode
SIP – Sensitive intervention point
ICE – Internal combustion engine
CCS – Carbon capture and storage

The New Economics of Innovation and Transition

Policy summary

Meeting the goals of the Paris Agreement requires unprecedented, policy-led transformations in multiple technologies and sectors. The greatest successes achieved so far in the low-carbon transition happened in ways that few people expected, using approaches that were not those recommended by standard economic analysis. To replicate these successes, we need to learn the lessons and think differently about the dynamics of change in our economies. Rather than seeing the challenge as one of managing difficult trade-offs between the pursuit of economic growth and the cost of cutting greenhouse gas emissions, we must improve our understanding of transformational change to appropriately include the potential for accelerated innovation, technology cost reductions, job creation and significant economic benefits. This means also changing how we appraise relevant policies. We need a new approach, to supplement traditional cost-benefit appraisal with new techniques, to understand the risks and opportunities of transformational changes.

The EEIST project, engaging researchers across Europe and major emerging economies, tackles this challenge by developing a framework to support decision-making through **Risk-Opportunity Analysis (ROA)**. Our flagship report 'The New Economics of Innovation and Transition: Evaluating Opportunities and Risks' reviews evidence and theory to explain the limitations of traditional appraisal methods and the rationale for the ROA, illustrating the framework across a series of historical and forward-looking case studies.

Recent transitions to clean energy technologies have succeeded beyond expectations

- Since 2010, wind energy has grown from under 1% to 10–15% of electricity in Europe and Brazil, with continuing cost reductions including dramatic progress offshore. Solar PV has expanded to similar capacities globally as costs have plummeted by 85%, driven initially by policies in Germany and the emergence of Chinese manufacturing. Similar cost reductions were secured from LED lighting in India through bulk government procurement programmes for affordable energy access. All three now offer among the cheapest ways of producing electricity, and light, across much of the world.
- These successful cases involved a range of policies. However, the policies that played the most critical role were neither public R&D, nor not the instruments that economists typically recommend as the 'most efficient'. Instead, they were policies that targeted resources directly at the deployment of these technologies – through subsidies, cheap finance and public procurement.
- The most widely used economic framework for public policy appraisal, cost-benefit analysis, did not recommend the use of any of these critically important policies. In general, these policies were implemented despite, not because of, the predominant economic analysis and advice.

The traditional processes for economic appraisal are not always appropriate

- Adding up costs and benefits presumes they are reasonably predictable and quantifiable with some confidence. But many of the most important benefits of a low carbon transition – like the creation and development of new technologies, supply chains, business models, jobs, and new markets – are not knowable with confidence. Omitting these elements from the calculation creates a bias towards inaction.

- A focus on current knowledge of costs and benefits overlooks the effects that policies can have on processes of change in the economy. This can neglect risks and opportunities, ignore the potential for policies to have self-amplifying or self-limiting effects, and miss the potential to trigger 'tipping points' and cascading changes.

- Policies that create change in the economy affect societies' interests in many ways. Jobs, air quality, climate change risks, energy costs and many other factors can be affected by low-carbon transitions. When all these are converted into a single metric (money), the decision about their relative importance risks being made implicitly; this can undermine transparency, trust and political robustness of decision-making.

Risk-opportunity analysis (ROA) offers a new way of assessing options

- Instead of only counting identified costs and benefits, ROA involves mapping both risks and opportunities. That means considering all the potential effects of a policy that might be important, even if a number cannot be put on them.

- Instead of only comparing the expected outcomes of policies at a moment in time, ROA also considers processes of change in the economy. This includes drawing attention to feedback loops – relationships that reinforce or oppose change – and how they can be strengthened or weakened. It can include looking for 'sensitive intervention points' where modest actions can have large effects.

- Instead of converting different kinds of outcomes into one metric, each in its own right can be assessed, so that the weighing up of different interests can be done transparently and deliberately by decision-makers accountable to society.

Putting theory into practice: reflecting on the past and looking forward

- From its historical case studies, the report finds that appreciation of the potential for reinforcing feedbacks to drive down the costs of clean technologies could have supported a strong case for investing in the deployment of those technologies, even when their costs were high.

- The historic transitions all involved an evolving mix of policies, and interactions of domestic with international developments

- Looking forward, the report demonstrates how these new ways of thinking can inform low carbon strategies for other sectors. For the transition to zero-emission vehicles, ZEVs, mandates may have the greatest impact by reducing multiple uncertainties throughout supply chains, but combinations of policies are likely to offer more than the sum of their parts. In the early stages of the transition to low-carbon steel, targeted deployment policies such as subsidies or public procurement are likely to be more effective than carbon pricing, but both together could be more effective still.

The international dimension is important

- Historic assumptions that emission reduction would necessarily involve net economic costs framed the diplomacy of climate change as a problem of burden-sharing.

- Undoubtedly, low-carbon transitions do involve costs and difficulties. But well-designed policies for innovation and transition also have potential to yield net economic benefits. The diplomacy of climate change can be transformed into a 'positive-sum game'.

- The new economics of innovation and transitions highlights opportunities for positive-sum collaboration. Coordinated action can create faster innovation, larger economies of scale, stronger incentives for investment, and level playing fields where they are needed.

- Some of these coordination gains are evident in the report's historical case studies, even though they may not have been pursued intentionally. With informed and targeted efforts, domestically and internationally, society could greatly accelerate progress in each of the emitting sectors of the global economy.

Technical summary

The countries of the world have never before had to tackle a challenge like climate change. Progress to date has been clearly inadequate, yet there have been important breakthroughs, notably in clean technology costs.

Our key finding is that these have been achieved despite, not because of, traditional approaches to policy assessment. They have been driven, principally, neither by public research and development (R&D) efforts, nor by policies enacted on the basis of traditional appraisals of economic costs and benefits – cost–benefit analysis (CBA).

Learning the lessons is vital to the future of global decarbonisation. This report does not lay out what needs to be done, but instead explores deciding how to decide what needs to be done in terms of specific policies for decarbonising key sectors. It offers principles for policy assessment in a real world where there are complex systems and important uncertainties, where no government policymaking is driven purely by climate concerns with unlimited financial and political resources, and no global decision-maker is focused on our collective long-term interests.

While drawing upon the evidence of our three historic case studies (**Box 1**) the approach developed in this report is grounded in strong theoretical foundations. These theoretical foundations explain two core problems with traditional CBA in the context of deep decarbonisation. First, CBA is impractical in this context, given fundamental systemic uncertainties which cannot be reasonably substituted by 'best-guess' or even probabilistic risk evaluation approaches. Second, it yields results which, in the context of the need for major transitions, are systematically biased towards the status quo.

BOX 1:
Innovation and transition in energy technologies: three case studies

- Once characterised as inherently inefficient, limited and expensive, wind energy has emerged at scale – increasing from under 1%, to 10–15% of electricity supplies in Brazil and Europe over the past decade, for example – along with steadily declining costs. More recently, the cost of offshore wind energy has plummeted. In 2012, an industry study suggesting that costs could be brought down by a third by 2020 was regarded as highly optimistic, and government support for expansion was strongly criticised; yet, driven by programmes for coordinated development and large-scale deployment, costs fell by 70% and it now forms the largest single element in the UK's electricity and decarbonisation strategy.

- The evolution of solar PV – by far the world's largest renewable resource – has been even more dramatic, transitioning from being "the most expensive way to reduce carbon emissions"[1] to offering "the cheapest electricity in history".[37] The German *Energiewende* played a pivotal role by creating market, industrial and financing structures at scale. Major price reductions ensued with the rapid growth of Chinese manufacturing, which then stimulated rapid deployment within China – and beyond. In addition to emission reductions, solar PV can in principle now support low-carbon development for some of the poorest people on the planet.

- For over a century, the world wasted energy by heating wires in bulbs to light our homes, offices and streets. Building upon initial international support for more efficient lighting, under the Kyoto Protocol's Clean Development Mechanism, India then developed its own programmes. In the wider context of bringing modern energy services to the wider population, policy for efficient lighting in India resulted in annual sales of light-emitting diode bulbs (LEDs) soaring from just 3m in 2012 to 670m in 2018. From 2015, driven by bulk public procurement along with efficient policy design, LED prices fell by 85%, cutting energy bills and emissions, and – as with solar PV – moving the technology from being the most expensive to the cheapest on offer.

CBA as normally practiced is appropriate for changes which are marginal to the underlying system and which do not significantly change the cost, nature or availability of subsequent options. It tends to downgrade the importance of factors which cannot be quantified. Deep decarbonisation, in contrast, involves innovation along with structural and systemic changes which are hard or impossible to accurately forecast or monetise with confidence. The nature of the problem demands a different approach.

From this combined research into theory and evidence, we draw the following principal conclusions:

1. For evaluating policies from which transformative change is expected, needed or intended, assessing opportunities and risks is more appropriate than the traditional, narrower focus on monetised costs and benefits.

The low-carbon transition is dynamic, long-term and comes with multiple uncertainties. While the costs of a given intervention may be reasonably well defined and bounded, the full long-term benefits of policies promoting low-carbon investment may be almost unbounded, and can include outcomes ranging from the direct and indirect economic benefits of induced technological innovation to multiple benefits of a more stable climate – in economic jargon, 'fat-tailed benefits'. Evidence can – and must – inform expectations and the potential for technology cost reductions (for example), but all long-term benefits cannot be plausibly quantified.

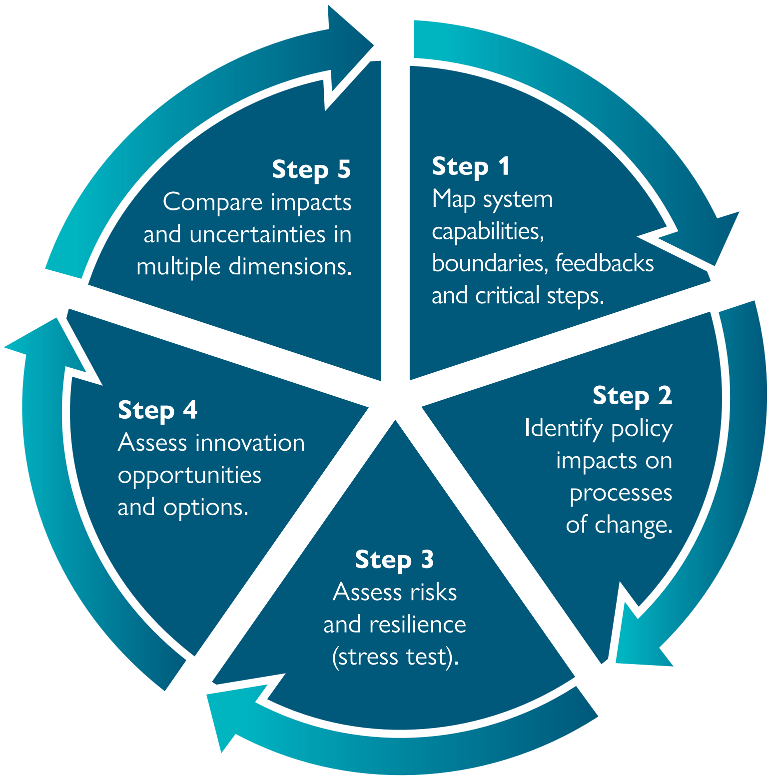
While cost estimates of large complex projects or programmes often prove optimistic, our three historic case studies demonstrate precisely the opposite in terms of key renewable energy and demand-side technologies. In tandem with policy-driven, large-scale investment, the cost of solar photovoltaics (solar PV) and highly efficient lighting fell by 85% in less than a decade; wind energy costs, including offshore, have also tumbled as a direct and traceable result of multiple policies. In many conditions, all three are now cheaper than the traditional incumbent, high-carbon or less-efficient technologies.

In all cases, growing market share combined with the internationalisation of the industry, including production and markets in major emerging economies, has been a critical factor in this progress. 'Experience curves', which link cost reductions to deployed scale, have been a better predictor of cost reductions than expert judgements often used to inform economic appraisals and modelling. The opportunities now being realised clearly outweigh the significant initial investment costs and risks of early deployment efforts.

Dynamic systems theories represent economies and technologies as interdependent and continually evolving. Schumpeterian theories of 'creative destruction' and modern insights on the structure and drivers of socio-technical transitions, highlight the obstacles to changes which can ultimately be economically beneficial, but which involve transitional costs and large uncertainties. Modern approaches to 'complexity economics' and agent-based modelling yield related insights. We cannot realistically know the future and there is no reason to assume that markets alone will result in a safe or least-cost trajectory, particularly in the face of global threats like climate change, even with the pricing of 'external' damages.

2. A structured approach to assessing opportunities and risks can inform effective, consistent and transparent decision-making.

Major changes to the status quo direction involve risks in order to exploit opportunities, neither of which can be fully or confidently quantified. A structured approach to navigating policy choices in this context, to inform effective, consistent, and transparent decision-making – a risk–opportunity analysis (ROA) approach – could usefully involve the following steps:



Step 1: Establish objectives, options, key system characteristics and system feedbacks. Define the objective within the target system (e.g. improving a specific technology within a given sector) and decide if the option being examined is 'mission-critical' to this objective. Establish the main characteristics, feedbacks and boundaries of the system and identify models available for analysing the system.

Step 2: Identify the impacts of policy options on processes of innovation and system change. Consider how policy options might affect innovation, infrastructure or other factors which may strengthen, weaken, create or eliminate reinforcing or balancing feedbacks, and whether or how this might change structural relationships between components of the system. Where historical data are available, assess the outcome of related past initiatives to inform the evidence based on system dynamics.

Step 3: Assess risks and resilience. Stress test the resilience of the system and the influence of the proposed policies regarding extreme, if unlikely, circumstances. Probe the most important ways in which the system could fail and the potential consequences with attention to cascading failures and tipping points, and the existence of low-likelihood, high-impact outcomes.

Step 4: Assess innovation and opportunity creation. Explore the ability of the policy to create or enhance options that could help the system evolve towards the goals established, in ways that capture economic and other opportunities. This includes potential technology and wider system cost reductions assessed through the various approaches identified, an analysis of the capabilities that may be developed and the markets that may be created, domestically and abroad. Large-scale programmes may also assess trade impacts, productivity improvements and resources and institutional implications.

Step 5: Engage decision-makers concerning the impacts and uncertainties in multiple dimensions. Impacts, degrees of uncertainty or confidence, and resilience estimates for each of the metrics adopted in Step 1 can inform decisions, with specific reference to strategic goals of the overarching policy and legal frameworks. The preferred strategy is determined by the appropriately appointed decision-maker based on a qualitative judgement of the nature and scale of the opportunities and risks of the policy under consideration. This will necessarily be a subjective judgement, since it incorporates a weighing of outcomes in different dimensions, informed by an objective assessment of likelihood and magnitude of possible outcomes in each.

3. Transformative changes involve a mix of policies which need to evolve over time.

No single policy instrument can plausibly drive the transitions required to reach net zero. Drawing upon a framework of three decision-making domains, we classify three broad arenas of policy:

- **Strategic investment**, principally but not exclusively by public authorities. This includes and builds upon R&D and other 'technology-push' investments, but typically extends well beyond this to foster the emergence of new technology industries at scale. These include targeted demand–pull policies, infrastructure, 'patient' state-backed finance, and coordination and institutional frameworks required to support the development of mission-critical options at scale.
- The structure of **markets and pricing**, including sectoral and financial regulatory frameworks and carbon/externality pricing, are likely to determine the pace of transition as successful developments move from emergence to a phase of breakthrough and diffusion, within and across countries.
- Policies that influence **norms and behaviour**, including public attitudes, may be relevant at all stages and will evolve, but may in particular do much to determine the scale at which new options are ultimately accepted in society, and potentially, their integration into wholly new markets with cross-sectoral developments.

Different transitions will involve different specific policies, in different specific combinations, at different times. In addition, transition processes may offer 'sensitive intervention points' at which modest interventions yield large, long-term changes.

4. Case studies on electric vehicles (EVs) and steel/hydrogen are illustrative.

Two forward-looking case studies serve to illustrate key features of the ROA approach. To support the analysis, we draw upon results of an 'ROA-consistent' numeric model – namely one which is based on principles of evolutionary economics with future developments determined by the contemporary characteristics of the system in key countries, and by a multitude of influences on decision-making which cannot all be represented in terms of a single, far-sighted 'representative economic agent'. While all results are contingent upon specific model structures and assumptions, this serves to illustrate key features of potential transitions in the major emerging economies engaged in the Economics of Energy Innovation and System Transition (EEIST) programme.

- **EVs**, despite so far accounting for barely 1% of vehicle miles travelled, have every prospect of dominating light vehicle transport in the major Asian economies within two decades (the region may overtake European efforts to electrify transport). EV life-cycle costs are already or will soon be cost-competitive with internal-combustion vehicles in China and India, and in the medium term are likely to become cheaper to buy (purchase cost) as well. Along with the direct impact of potential 'EV mandates', sensitive intervention points for policy include addressing up-front purchase costs for consumers and rapid development of charging infrastructure, as well as the level of fuel duties which are naturally higher for oil-importing economies. Brazil, however, may face a very different future for its transport systems (especially outside the major urban centres of the south-east), given specific national characteristics and historic and current policy choices: there is no one-size-fits-all solution for the future of transport, and this may be indicative of prospects across much of the American continents.
- **Low-carbon steel** technologies are at a much earlier stage of development, and costs and prospects are uncertain, but they are mission-critical to the goals of the Paris Agreement. In many (but not all) contexts, the future of low-carbon steel is likely to be tied to the development of green hydrogen systems; India, despite a preponderance of highly carbon-intensive steel technology at present, is in principle well placed to help drive forward hydrogen-based steelmaking at scale. A combination of policies is essential to drive development, including, ultimately, integration with 'green hydrogen' strategies and costs. Diversity of steel technologies, policies and trade patterns may persist for decades, and there is a central role for demand-side procurement alongside 'circular economy' policies. Overall, the risks are significant but the opportunities are enormous.

Given the scale of steel use in vehicles, and the potential role of hydrogen in some other sectors (including heavy-duty transport), the shape and pace of the low-carbon transition in these two sectors (and others) could to some extent be co-dependent. Identifying the risks and opportunities in such co-evolutionary dynamics can help identify potential sensitive intervention points – e.g. exploring the systemic implications of supporting fully zero-carbon vehicles, including their materials.

5. International collaboration will be key to accelerating transitions in some technologies and sectors.

Under the traditional economic perspective that reducing greenhouse gas (GHG) emissions is necessarily a (local) economic burden, the diplomacy of climate change has been widely seen as a problem of burden-sharing – a 'negative-sum game'. In reality, the incentives for countries (and companies) to engage in the transition depend on their share of economic risks and opportunities. Zero-emission technologies and systems can be cheaper and perform better than those based on fossil fuels. This does not make it easy, quick, or even cheap – the renewables revolution has been built on decades of development and up-front investment totaling hundreds of billions of dollars.

Yet, the economics of innovation and transition offer a 'positive-sum game' in which international cooperation could reduce risks and increase economic benefits to the participating countries (and companies), at the same time as reducing emissions. Each of our three historical case studies shows the importance of internationalisation in the course of their development; net benefits could be enhanced with conscious international cooperation. Areas of potential net benefit could comprise:

- ***Shared learning: coordinated development and testing.*** Sharing learning between countries and industries can reduce individual risks and accelerate progress towards viable solutions. Notwithstanding intellectual property concerns, cross-learning and technology spillover were vital in the early development of solar PV and efficient lighting, and conscious coordination was even more evident in the development of offshore wind energy. The same principle holds for sectors currently in the early stages of transition, such as steel, and others not directly described in this report, such as agriculture and aviation.

- ***Economies of scale: mutual policies to expand deployment.*** Measures and commitments to deployment can accelerate economies of scale and corresponding cost reductions, as observed in our case studies. Every country can contribute to this progress, combining local and global progress. Cooperation can also take the form of practical assistance with the policies that reform markets, mobilise investment and bring down the costs of deployment within a given country.

- ***Financial transition.*** An often-overlooked dimension of cost reduction has been cheaper finance as confidence grows. To accelerate global adoption, the terms of low-carbon finance available to developing countries will be important to overcome the 'finance trap' of high interest rates which arises from – but also exacerbates – perceived technological, business and country risk, particularly for newer technologies which do not have established, deep domestic and international financing structures. Public resources, when deployed internationally, can leverage private finance into new, global technology markets.

- ***Standards and incentives: embedding change throughout the sector.*** Coordination on standards could help to overcome barriers to first deployment created by international competition, especially where zero-emission technologies may be more expensive than fossil fuels for extended periods. This would in turn accelerate the global deployment of zero-emission technologies in these sectors and bring down their costs more quickly.

These potential gains are huge. As well as accelerating transitions in each individual sector, international cooperation may be able to activate tipping points that lead to cascades of change across sectors and throughout the global economy, in a manner similar to large-scale industrial transitions of the past.

Just as the dangers of climate change are not evenly spread around the world, neither will the costs and risks of transition fall evenly. Issues of historic responsibility and differing capability for action are no less salient than before. However, international cooperation does not just offer routes to minimise the risks of climate change itself – it also offers the prospect of redirecting investment from high-carbon risks to low-carbon progress, and maximising the opportunities associated with the global transition to low-carbon economies.

1. Traditional approaches to policy appraisal

Responsible policymakers generally seek to pursue actions for which the expected benefits exceed the costs.

Over the years and in many countries, this simple principle has been translated into a technocratic approach involving efforts to quantify expected benefits and costs in ways which can be aggregated and compared on a common basis, generally in terms of monetary equivalence.

The resulting approach to policy appraisal that dominates in many countries – cost–benefit in a formalised sense of *aggregate, monetised* CBA – has gained widespread adoption and proved useful in many domains. It is dominant in Organisation for Economic Co-operation and Development (OECD) countries, and as our research shows[i], it is used extensively in key emerging economies such as China, India and Brazil, particularly to assess the financial case for projects, programmes and policies. The approach weighs estimated costs against the direct monetary (or estimated monetised-equivalent) expected benefits, although often without a common approach to application between sectors. Such monetary and easily monetised factors may often be complemented by recognition of other aspects, including the impacts on different groups in society (such as people on different income levels, of different ages, or who live in the city or the countryside), in addition to wider political considerations. However, in practice these may be seen as secondary compared to headline numbers which, for example, finance ministries can use as a simple screen to prioritise expenditure requests.

There are significant limits to what such formalised CBA can sensibly assess. These techniques best suit situations in which the major costs and benefits can be readily measured, quantified and compared. This is more plausible when assessing challenges and changes of modest scale – which are relatively short term and, in economic terms, 'marginal' to the economic system overall. This section briefly outlines the foundations and some of the more familiar limitations of the traditional approach, and then focuses on the core concern of this report: the limitations of traditional CBA in informing policy for transformational changes.

1.1. Classical approaches to cost-benefit analysis

Theoretical foundations

CBA is a tool for policy analysis. It does not, in principle, depend on any particular economic theory or doctrine.

However, in standard and widely used economic theory, the 'cost–benefit test' is generally seen to rest on the foundational principles of welfare economics and the concept of a social welfare function (**Box 2**), where identifying the optimal strategy through CBA is intended to maximise utility. This involves comparing two cases – with and without the decision in question – with their respective measurable costs and benefits. A first key underlying assumption is that the changes under consideration are small in relation to the overall system – 'marginal'.[2] A second key assumption is that the impacts of these changes can be reasonably quantified and numerically aggregated. The overall system itself is assumed not to be changed. If these marginal net benefits (ie. of change 'at the margin') are positive, the proposed reforms should be accepted, since they are welfare-improving.[3, ii], Embodying this simple and intuitive rule[4], CBA has become a widely used tool for informing regulatory and policy decisions.

[i] These insights derive from ongoing work by the EEIST project, and publications will result in future examination of these issues.
[ii] This can be found by finding the maximum SWF subject to constraints.

BOX 2:

Fundamentals of traditional economic cost-benefit appraisal (CBA)

The use of CBA to maximise social welfare is built on the foundation of welfare economics, which is focused on determining how best to make social decisions. Starting from the assumption that individuals and their preferences matter and can be measured, standard welfare economics makes use of an imagined 'social planner' that optimises individual choices on the basis of a social welfare function (SWF) which aggregates individual preferences. In this framework, policymakers aim to maximise collective 'utility', subject to constraints (such as budgetary limitations). Distributional goals are considered by choosing the specific form of the SWF, with different weights assigned to different individuals (or different classes of individual in practice). For instance, higher weights may be assigned to people with lower incomes.[iii]

Any social decision involves some consideration of multiple dimensions (impacts on different people, at different points in time and in different domains of wellbeing). Defining an SWF is a possible way to approach this[iv], but not the only way. Theoretical alternatives have been discussed, such as the Pareto criterion, which requires that a reform only be accepted when nobody becomes worse off and at least one person benefits from the proposal. However, virtually all practical policy reform or public projects typically incur net costs to at least some individuals, and therefore few policy proposals are likely to pass the Pareto criterion.[3] In the 'potential Pareto improvement' proposition, Kaldor (1939)[5] and Hicks (1939)[6] assume that potential winners and losers of the policy could compensate each other such that the policy is worth proceeding with if net welfare changes are positive. In practice, it is difficult to make these transfers materialise. The SWF approach has thus always been seen as most practical, and has dominated policy appraisal in the UK, the US, Canada, Brazil and many more countries around the world.

To calculate and compare marginal social costs and benefits over different people at different points in time implies using a unique standard unit of accounting. Welfare changes are frequently measured as the amount of money that one has to pay/receive to remain equally well off before and after the changes, which can be estimated as willingness to pay for a potential gain or willingness to accept compensation for a potential loss, depending on the specific circumstances.[7, v] A discount rate is used to weigh and compare impacts across time on the assumption that societies attach more value to something now than in the future, for a variety of reasons.

Different methods have been developed to calculate values for traded and non-traded goods. Traditionally, when there are complete and undistorted markets, market prices are considered useful indicators of the marginal social costs/benefits of small changes. Where markets are missing, or imperfect, stated preferences can be a useful *ex ante* approach and revealed preference is commonly used *ex post*.[8] Stated preference approaches typically involve asking people directly what they might pay to avoid, or accept as compensation for, a given impact (questions which, unfortunately, often yield quite different answers). This assumes that people are willing to pay for non-market goods through either money or other market goods. The latter approach may use, for example, the amount of money people spend on masks and air purifiers to estimate how much they value clean air.

[iii] Preferences are implicitly assumed to be cardinal, and interpersonal comparisons of utilities are possible, which necessitates social value judgements regarding equity.[3]

[iv] Using merely ordinal information, the Arrow's Impossibility Theorem shows that there is just no easy and sensible way to aggregate individual preferences and to obtain a consistent social decision.[129,130]

[v] A convenient approximation of welfare changes is 'consumer surplus' (CS), which can be directly derived from observed demand but is only valid under the assumption of trivial income effects, e.g. individual demand of goods does not change substantially as wealth increases.

However, CBA requires sufficient data and comparable metrics to reasonably estimate overall costs and benefits. Many of the resulting challenges are well known.[9–11] CBA is often criticised for 'reducing everything to money'. In practice, some of the challenges quickly become clear; typically, willingness-to-pay differs considerably from willingness-to-accept compensation (**Box 2**), with no objective way to choose one over the other. This reflects the inherent difficulty in measuring the current welfare of individuals, let alone groups. Even more challenging is to assign collective welfare to a distant future following major transformations. There is long-standing debate about the discount rate appropriate for very long-range problems like climate change.[12–16] Most recent economic literature suggests applying risk-free, public and long-term interest rates when evaluating climate change[17–20], which gives higher weight to future impacts than many earlier studies.[vi]

However, while the above challenges matter, they do not fully capture the core problem. For deep decarbonisation, policies aim to transform our energy systems and set them on a new path. This contrasts sharply with the implicit assumption of traditional CBA, that the impacts of proposed changes are marginal and leave the economic structure mostly unchanged. The CBA approach also assumes that those impacts are reasonably identifiable and quantifiable, allowing us to numerate an 'optimal' climate policy. What should policy analysts do when these two assumptions are not valid?

1.2. Goal-setting in the international arena

Given the scale and scope of climate change, global negotiations have in practice established goals based on other principles.

These include security in the face of planetary-scale risks and equity, given that the problem has largely been caused by rich countries while poorer countries may suffer disproportionately. Thus, the United Nations Framework Convention on Climate Change (UNFCCC) 1992-agreed goal to "to prevent dangerous anthropogenic interference with the climate system" in the climate system, translated some 23 years later into the Paris Agreement's core aim to keep warming well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels".[21,vii]

In contrast, options and efforts to reduce emissions to achieve these goals have generally been framed in classical economic terms, focused on assumptions about costs, with a relatively static, burden-sharing perspective.

The previous agreement, the 1997 Kyoto Protocol, circumvented the imponderables of economic CBA and equity by negotiating mid-term emissions targets for rich countries which were legally binding (upon ratification). The fact that participating countries had to (and did) comply prompted a range of action, including encouraging some of the more transformative developments sketched in our case studies. With the need to globalise action, the Paris Agreement had to abandon legally binding national emissions commitments, which may render implementation policies more subject to national cost-benefit appraisal, since there is no specific binding national requirement.

[vi] Based on this emerging consensus, expert elicitations suggest a discount rate around 2–3%[131], lower than in many of the earlier efforts to conduct CBAs of climate change. The US Interagency Working Group on the Social Cost of Carbon used 3% as its central value.[132–134]

[vii] UNFCCC (1992)[135]: specifically UNFCCC Article 2 (Objective): "to achieve … stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."

The consequence has been to posit ambitious agreed global goals against a widespread assumption that such goals will: be costly to deliver; require a huge effort of international coordination to address burden-sharing; and that the most efficient way of delivering the goals will be to work incrementally up the 'cost curve' of global abatement options, starting with the cheapest. Many economic perspectives would add an assumption that mitigation should preferably be driven by a rising and internationally coordinated carbon price.

This mix of risk-based thinking in setting the goal, and traditional equilibrium/marginal cost-based thinking in terms of mitigation economics, risks setting the system up for failure. It embodies an intellectual inconsistency, which indeed at present is materialising in inadequate national ambition and insufficient implementation. Based on science, risk and precaution in the face of a global threat, goals have been agreed which demand transformative rather than marginal change. A zero-carbon transition – implicit in any scenario that stabilises atmospheric concentrations and temperatures – will involve wider changes in the structure of the economy, behaviours, and the nature and composition of industry and infrastructure. Yet formalised CBA rests fundamentally on the opposite assumption: it evaluates the costs and benefits of a specific action on the assumption that these are knowable, and marginal to an underlying system which is unchanged – or more specifically, that the action itself does not contribute to wider, deeper and more strategic changes.

In such cases, formalised, monetised CBA is like comparing apples and oranges, or worse. Formalised, monetised CBA rests on the assumption that costs and benefits are knowable and sufficiently known, and little else changes. Yet in the case of deep decarbonisation, the intent, expectation and reality is that our energy systems – a fundamental part of our economies – need to change significantly, and uncertainty is endemic. Prices, demand, productivity or other macro variables are assumed in CBA to be unchanged by the application of the policy. Yet deep decarbonisation will be entwined with innovation and huge changes in energy markets, invalidating the original assumptions, and hence conclusions, of classical CBA based on implicit assumptions of marginal change.[2,8]

1.3. Stages of innovation

Innovation causes economic growth and development. Technology innovation is therefore part of the puzzle, but a focus on innovation needs to start from recognition that it is not something separate from the economic system, with the government role partitioned off in a box labelled 'R&D'.

Innovation is a complex, multi-stage and iterative process, and is part of the economic system itself. The outcomes of investment in innovative activity cannot – by definition – be predicted; however, they regularly materialise and improve the everyday lives of people. Being hard to quantify, the impacts of innovation are often ignored in CBA. But how should they be considered in policy appraisal?

The innovation process is typically represented in terms of an 'innovation chain'. **Figure 1** illustrates such a chain, in which all the stages are linked, with feedback as earlier stages are informed by learning in later stages. Innovation combines forces of technology-push and demand-pull, the latter tending to be more important as a technology moves through the chain. The impact of varied policies on multiple metrics of innovation is demonstrated in extensive studies (as reviewed by Peñasco et al. (2021).[22]).

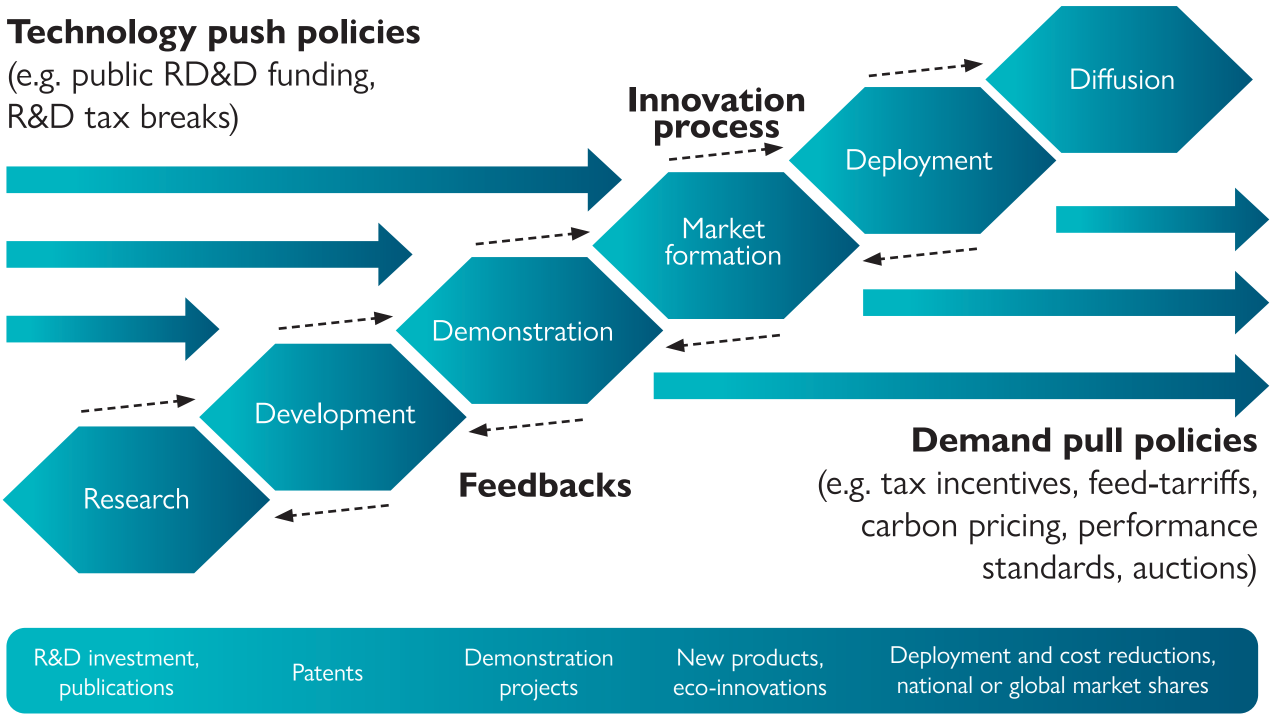


Figure 1: The innovation chain
The bottom bar contains some of the indicators typically used to understand activities along the different stages of the innovation process.[22,23]

Economically, the later stages involve larger scales and generally bigger investments. This can be particularly true of the stage in which technologies are actively deployed to help drive cost reductions through learning-by-doing and economies of scale in technologies, supply chains and industries. This emerges as an important stage in our case studies, supported by extensive and more general evidence documented in another systematic review of the literature on induced innovation.[24]

Any method of appraisal must account for the fact that analysts have a limited ability to predict the future, and some uncertainty (or unquantifiable risk) is inherent in innovation. Recent studies document that expert judgement on technology forecasting has often been wide of the mark and marred by systematic bias depending on the type of technologies. Meng et al. (2021)[25] suggests that, over the past 15 years, some model-based forecasts, drawing upon learning-based models, do better (in part by indicating a wider range of uncertainty that challenges the frequent conservatism of expert forecasts).

They also show that (at least during this period), with the exception of nuclear, the medians of forecasts have underestimated the pace of innovation. Others emphasise the need for deeper understanding of innovation processes in the structure of technology cost forecasting.[26]

Thus cost-benefit appraisal must deal with inherent risks and uncertainty associated with future costs and benefits.[viii] For situations of limited uncertainty and confidently quantified risk, the standard CBA approach would deal with uncertainty by summing probabilities multiplied by the scale of different outcomes.[27] Where uncertainty is large or risk is not quantifiable with reliable probabilities, guidance is to use sensitivity analyses, testing the robustness of results by systematically varying uncertain parameters.[7] Yet these ultimately implicitly use probability distributions, from which variations are drawn, and these distributions may be simply unknowable – 'deep' uncertainty. [ix]

1.4. The potential for inherent bias in traditional cost-benefit appraisal

The Intergovernmental Panel on Climate Change (IPCC) has described deep decarbonisation as requiring "rapid and far-reaching system transitions" in each of the GHG-emitting sectors of the global economy – unprecedented in terms of scale.[28]

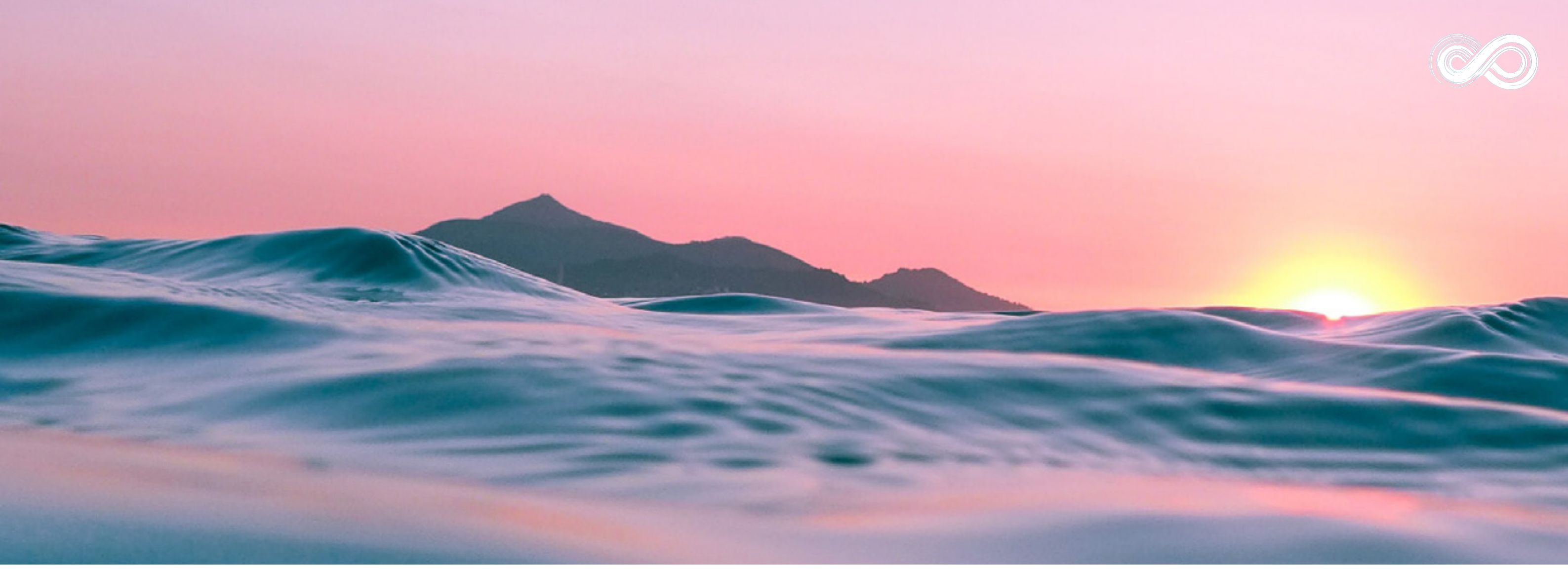
In contrast to CBA based on marginal changes in particular variables, much of the transformation of economies and societies required to achieve net-zero emissions is irreversible and far from marginal. Such transitions are unavoidably dynamic, long-term, highly uncertain and involve multiple variables (and constraints) in the economy undergoing significant change over the relevant period. Non-marginal changes may bring in new products and business models, move macroeconomic variables and significantly alter human and geospatial relationships in the economy.

Theory and evidence show that, if changes are not small, errors from using conventional CBA can be significant.[2] This has also been recognised in recent revisions to the UK government guidance on policy appraisal, known as the Green Book.[29, x]

[viii] The use of language varies in the literature. In this section we use the term 'risk' following standard definitions in risk assessment (e.g. ISO risk-management standards) in which probabilities can be identified but are not necessarily quantifiable, while 'uncertainty' refers to limitations in existing knowledge and to the ability of humans to generate it.

[ix] In economics, alternatively called Knightian, Keynesian or deep uncertainty.

[x] A review of the UK government's policy appraisal guidance carried out in 2020 recognised many of these limitations, and resulted in new guidance for policymaking intended to create transformational change. This emphasised the need to consider system dynamics, including feedbacks and tipping points, as well as uncertainty and risk.[136] Section 4 of this report, on ROA, can be read as a proposal for how to put this guidance into practice.



However, notwithstanding unavoidable uncertainties, the most obvious justification for CBA is that it is still better to estimate costs and benefits than not. A crucial question, however, is whether CBA could *mislead* policy appraisal though bias. Innovation is by its very nature unpredictable, with the exact probability of success unknowable. In contrast, the immediate costs of policies are usually more easily quantifiable, making them more likely to be included with higher detail in the analysis. This generates several sources of likely bias in CBA in such contexts.

One is what became known as the McNamara Fallacy – or more formally, the quantitative fallacy – the risk of according "what can be counted" more weight than "what may count".[xi] Another is a status quo bias in which CBA downplays (or does not include) the potential long-term benefits of technological change, such as technological spill-over and the creation of new industries.

Cumulative innovation action creates resources that become usable thereafter in the economy, and is a major contributor to welfare.

Pooling the up-front risks of innovation using a venture capital approach is demonstrably effective at generating economic and social returns.[30] Thus, for the low-carbon transition, CBA could be missing a large part of the relevant picture – resulting in a bias toward inaction.

Moreover, if we neglect the likelihood of innovation and structural change induced by mitigation policies, we may assume the cost of emission cutbacks will be enduring, when they actually turn out to be a transitional investment in changing technologies and systems, and overcoming inertia.[31]

A key feature of transformational change may give food for thought. While minor components of a successful transformational agenda may appear marginal at face value, the sum of many well-coordinated, small innovative projects may become transformational in the broader and longer-term picture. Policy appraisal carried out on a marginal-change basis and applied to the building blocks of a transformational agenda will fail to see the landscape emergent from assembling the pieces of the puzzle. The outcome of a successful sustainability transition is bound to be more than and different from the sum of the expected impacts of its constituent parts within their specific narrow scopes.

The design of alternative tools and methodologies is, of course, not straightforward. Not least, CBA benefits from a well-established tradition of moral philosophy dating back to the 18th century, from which much of the present-day science–policy interface originates. While transformational change has happened many times in the past and spawned important (but very different) strands of economic thinking – such as creative destruction as part of the innovation process – transformation on the scale implied by the sustainability transition may never before have been such a clear and explicit policy objective. Uncertainty – and opportunity – needs to be built into the fabric of analysis. To demonstrate why, we turn to three recent case studies.

[xi] The attribution is to the belief of the then US Defence Secretary, Robert McNamara, as to what led to the US's defeat in Vietnam – his own focus on technical appraisal based on things that could be measured, like the number of Vietcong soldiers killed, rather than factors that couldn't be measured, like the sentiments and reactions of the local population. The social scientist Daniel Yankelovich (in *Corporate Priorities: A continuing study of the new demands on business*, 1972[137]), characterised it as: "The first step is to measure whatever can be easily measured. This is OK as far as it goes. The second step is to disregard that which can't be easily measured or to give it an arbitrary quantitative value. This is artificial and misleading. The third step is to presume that what can't be measured easily really isn't important. This is blindness. The fourth step is to say that what can't be easily measured really doesn't exist. This is suicide."

2. Historic case studies

Good science starts with evidence.

This section summarises case studies of radical changes in three key energy technologies: wind energy, solar PV and efficient lighting. Rather than tell the general global story of technology progress, which is now well covered in the literature, we look at how key decisions and strategies helped to drive these transformations. In each case we identify interactions between programmes in developed countries and major emerging economies – the latter focusing on wind in Brazil, solar PV in China and efficient lighting in India, respectively.

2.1. Wind energy in Europe, Brazil and the UK

Over the last two decades, the amount of electricity generated by onshore and offshore wind farms has increased dramatically, while the global average cost has roughly halved since 2010 (**Figure 2**).

Onshore wind, the more mature of the two technologies, now costs less than new fossil fuel capacity in most regions with good wind resources. Even offshore wind, once thought to be impossibly complex and expensive, is increasingly competitive. This outcome is the result of a series of decisions and actions by policymakers and public sector actors over the last few decades, taken on the basis of strategic considerations rather than standard CBA.

[xii] Synthesis of case studies by Paul Drummond (UCL, UK) and by João Carlos Ferraz (Federal University of Rio de Janeiro, Brazil) and Luma Ramos (Boston University, US). See Online Appendix 1.

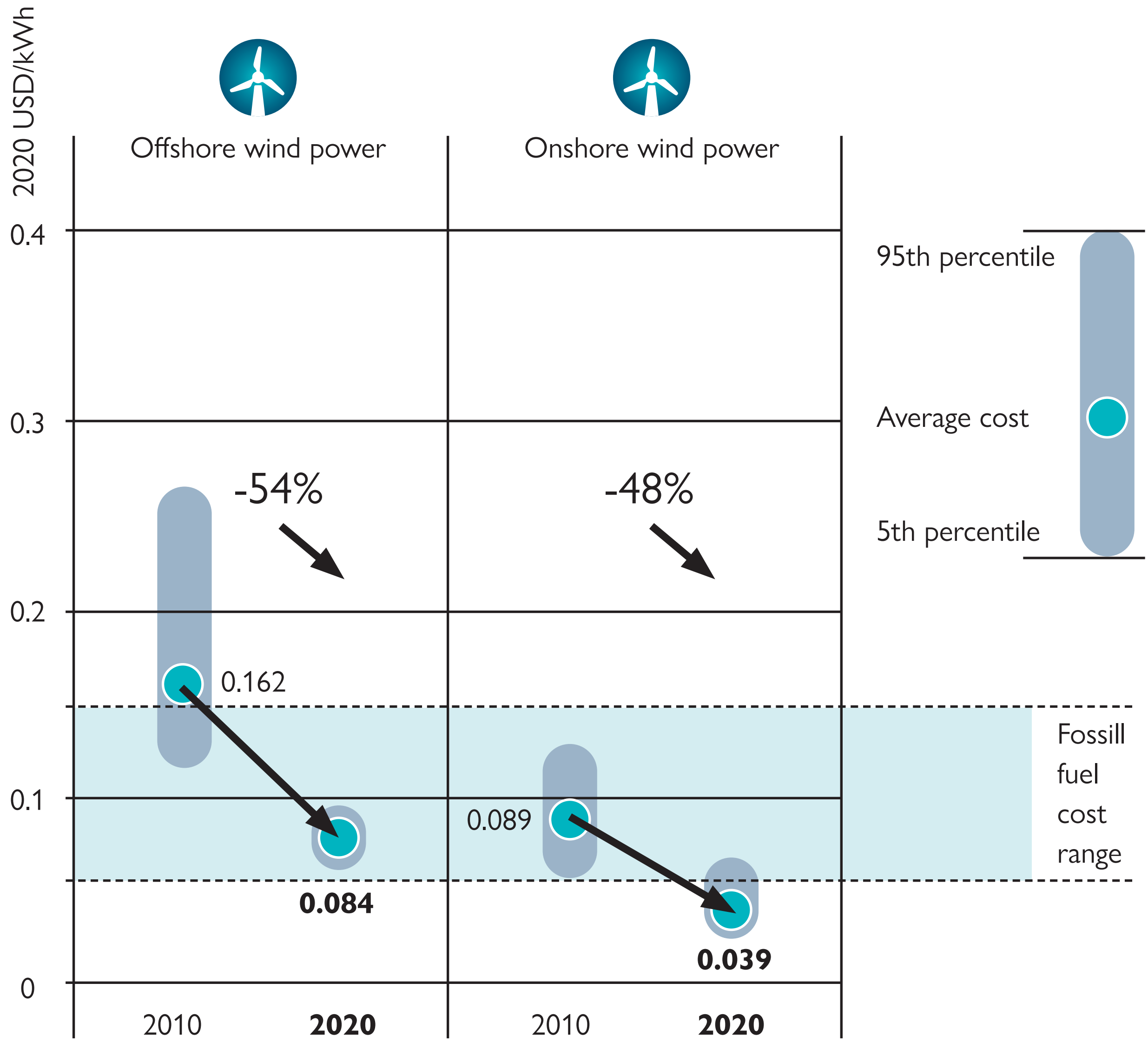
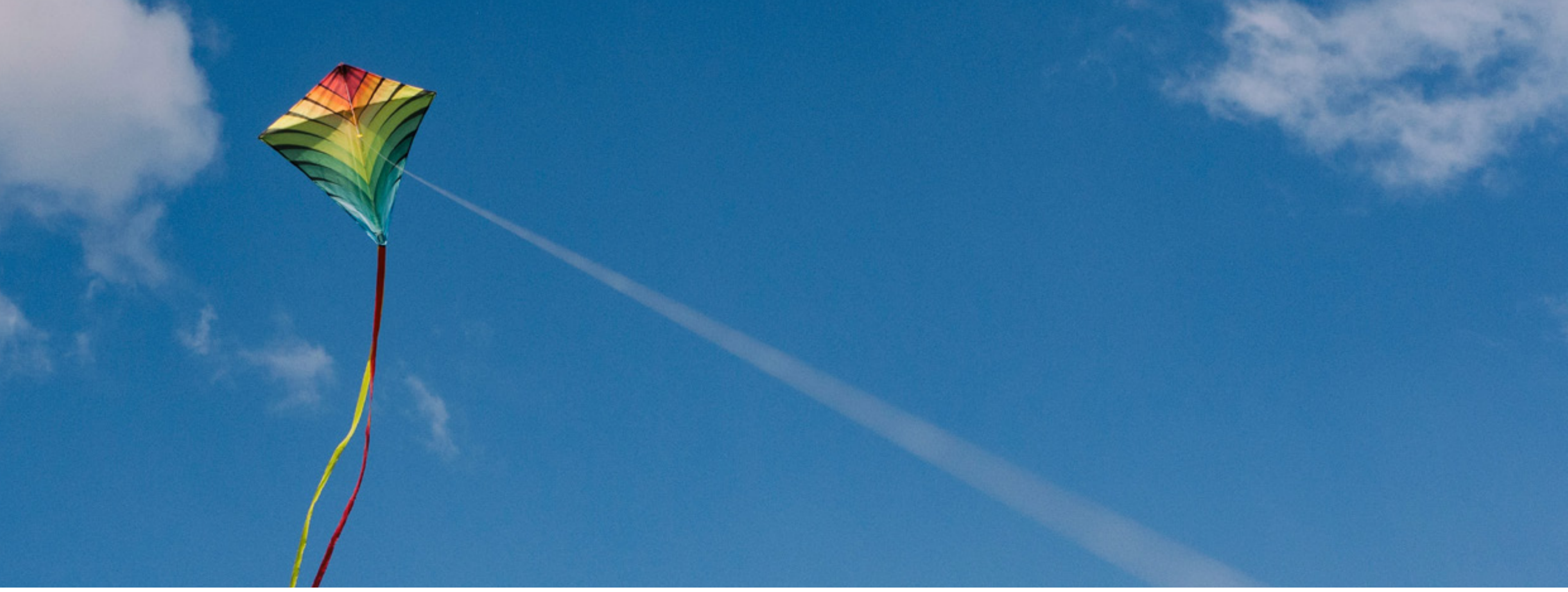


Figure 2: Range in of wind energy generation costs, 2020 vs 2010
Source: IRENA, Renewable Power Generation Costs in 2020 (p. 15).[32]

The development of modern, commercial onshore wind technology is rooted in response to the oil crises of the 1970s, and the search for alternative sources of energy. Many of the early efforts emphasised R&D, with some of the big aviation and engineering companies like Boeing and General Electric getting R&D grants to develop and demonstrate experimental turbines at scales which at the time were unprecedented – 1 to 3 megawatts (MW) – but correspondingly high cost and high risk. In essence, these failed.

In reality, the early developments which succeeded were led by California and Denmark. The latter built on a long tradition and at a much more modest scale, but supported test facilities, standardisation and resource mapping, with community involvement to garner public support (and local employment) in a cycle of gradually increasing size and reliability. Legislation in California created a market for such turbines, which helped to finance expansion of the industry. Building on the technological developments during this time, across the late 1980s and 1990s other European countries (particularly Germany, but also countries such as the Netherlands and the UK) began to support development and early deployment of wind energy (initially onshore, but later offshore) to meet early GHG and renewables targets, as well as for energy diversification and security.[33]

These early markets allowed significant technological advances to be made, with substantial reductions in costs, learning-by-doing and development of industrial capacity. By the early 2000s, onshore wind was becoming cost-competitive with fossil fuel-based incumbents in some countries, though it was still a tiny part of generation, and almost non-existent in developing countries. Offshore wind, however, remained relatively immature and substantially more expensive.



Onshore wind and the role of public development finance innovations in Brazil

In the 2000s, the largely hydro-dependent Brazilian electricity system faced a crisis from increasingly variable and unpredictable rainfall patterns, combined with high fossil fuel costs at the peak of the global commodity cycle. An extended period of drought from 2001 disrupted the hydropower supply, which previously provided more than 75% of electricity generation in Brazil. In response, the Electricity Crisis Management Board was established, which initiated the first public incentive programme to promote wind energy in Brazil. This – learning from initial failure – led on to an incentive programme, PROINFA.[xiii] By 2004, new policy directives were introduced with three objectives: to expand and diversify the energy mix, ensure security of supply, and amplify access to energy by the Brazilian population at affordable tariffs. PROINFA included a local content requirement (described as the 'equipment and services nationalisation index') of 60% and 90% for the first and second phase, respectively. This constrained supply during the first phase of the programme but also supported a more robust local wind power manufacturing industry.

Brazil has a vast wind energy resource, with some of the best resource in the relatively underdeveloped northeast regions. The government turned to wind energy as a strategic option to help expand and diversify its electricity system. Brazil first introduced regulations allowing utilities to contract generation through long-term power purchase agreements for a fixed price, awarded via auctions. The 60% nationalisation index was maintained as a requirement to access funding from the Brazilian Development Bank (BNDES).

This was further supported by infrastructure investment programmes such as the Investment Pilot Project (2005) and the Growth Acceleration Program (2007). Later, an unregulated market was created under which the terms of energy acquisition were left to bilateral, private agreements.

Internationally, the timing of the Brazilian push for wind energy was auspicious. Before 2008, most activities were concentrated in Europe and North America. As the Global Financial Crisis in 2008/9 curtailed support in these regions, the industry explored new markets to maintain growth. Brazil was experiencing largely favourable macroeconomic conditions (with an annual average GDP growth of 3.7% between 2004 and 2015) and increasing demand for energy, along with a policy drive for energy diversification. Given international and local market trends in the technology, onshore wind energy was well placed to benefit from the new market regulations.

This policy framework, and the growth in onshore wind it induced, were supported by a well-established institutional framework, with the participation of the policy-setting authority (Ministry of Energy), a long-term planning institute (Empresa de Pesquisa Energética), the regulatory agency (Agência Nacional de Energia Elétrica), Eletrobras, the state-owned electricity generation company, and BNDES. Investment costs tumbled and a significant supply chain industry has developed, employing 150,000 people. This development resulted from the combination of a stable market for an established technology, and policy and institutional drivers with financial clout, particularly BNDES (**Box 3**).

[xiii] Incentive Programme for Alternative Electricity Sources (Programa de Incentivo às Fontes Alternativas de Energia Elétrica – PROINFA).

BOX 3:

Brazilian wind energy: the role of the Brazilian National Development Bank (BNDES)

Historically, and for institutional and macroeconomic reasons, Brazilian interest rates have been high, and national private financial markets have lacked depth and maturity, impeding long-term investment finance. Over the years, Brazilian authorities promoted policy instruments to allow a public institution, BNDES, to address this problem. Between 1994 and 2017, a specific interest rate was introduced to guide BNDES loans (the TJLP), defined by the Brazilian Monetary Council (independent from and systematically lower than the market rate defined by the Brazilian Central Bank). BNDES thus could finance long-term investment projects and the development of a local capital goods and services industry.

As interest rates reduced and energy market dynamics changed with privately settled, shorter-term contracts coming to the fore, private actors started to emerge as sources of finance. However, by adapting its finance models to the new context, BNDES still provided competitive financing for onshore wind developments. Overall, between 2006 and 2019, BNDES financed around 80% of onshore wind developments in Brazil, with loans worth US$ 15.2bn, leveraging private finance worth approximately US$ 28.5bn.

To benefit from BNDES's terms of credit, investment projects must be sourced from accredited local suppliers. During the early years of the deployment of onshore wind in Brazil, few local producers were accredited. As wind energy investments expanded, criteria for accreditation expanded to incorporate parameters such as quality, efficiency and timely delivery, to induce supply chain learning and allow capacity to build. Such experiences with the wind industry, among others, led BNDES to abandon its traditional accreditation mode and to place local capabilities and efficiency as the core criteria for supplier accreditation across different investments and sectors.

Between 2010 and 2020, onshore wind in Brazil increased from negligible levels to around 17 GW (1 GW = 1,000 MW) of deployed capacity – generating close to 10% of all electricity in the country. The Brazilian onshore wind supply chain now consists of more than 100 firms, including six wind turbine producers.

Policy, innovation and cost reduction in offshore wind in the UK

While the entry of countries like Brazil (and China) into the global wind energy business helped to secure the technology as a new global energy source at scale, the prospects for offshore wind energy were more problematic. Taking large and complex rotating machinery into harsh offshore environments was clearly a daunting challenge. National conditions in the UK – with a huge theoretical potential, particularly in the North Sea, combined with extensive offshore engineering capability and growing local resistance to onshore wind-propelled the country to help pioneer attempts to go offshore. Some early assessments in the UK offered optimistic projections on paper, but the initial trials were not encouraging: the cost of the early offshore wind farms were around £170/MWh in 2008, several times the cost of the existing generation sources.

Yet only a decade later, the UK was able to issue contracts for offshore wind at around £40/MWh for projects coming fully online by 2023, making it competitive with fossil fuel generation and effectively subsidy-free (or even subsidy 'negative' – see next page). This outcome is largely the result of strong, well-targeted and sustained policy support from the UK government.

With a target for 10% of electricity from renewables by 2010, in 2002 the UK government introduced the Renewables Obligation (RO); a tradable green certificate mechanism providing subsidy in addition to the market price of electricity. The ambitious target ensured that these certificates traded at a price cap, which provided confidence to investors who, because the RO was technology-neutral, favoured the construction of mature, lowest-cost renewable technologies such as onshore wind.

In response to evidence that this was generating large profits for onshore wind while failing to stimulate more risky and expensive offshore developments, in 2009 the government introduced technology 'banding'; awarding more RO certificates to less mature technologies, notably offshore wind, to encourage their development.[xiv] Two other key enabling policies and measures were introduced along with this. The Offshore Wind Accelerator, developed and managed by the government-backed Carbon Trust, brought together nine leading offshore wind developers to accelerate commercialisation and cost reduction across the supply chain. Then, underlining the potential, the Crown Estate auctioned rights for seabed space sufficient for over 32 GW of offshore wind capacity and invested £80m in co-funding to improve understanding of offshore wind development.[xv]

The stability, long-term security and relative generosity of the subsidy provided by the RO allowed developers space to experiment, for the industry to form, core technical knowledge to grow and 'learning-by-doing' to develop across the supply chain (including in the financial sector). At this stage, the absence of mechanisms to induce competition between developers also encouraged collaboration, supported by the Offshore Wind Accelerator in particular – but the cost of support escalated as the scale grew.

Offshore wind's breakthrough

In 2013, a comprehensive UK Electricity Market Reform replaced the RO by a system of fixed priced, 'Contracts-for-Difference' (CfD).[xvi] Reflecting the lessons of the RO, separate 'pots' of funding were created: one for mature technologies, and one at higher prices for less mature technologies (including offshore wind).

At an initial cost of £140/MWh, the government issued a volume of contracts sufficient to secure investment in a major wind turbine manufacturing plant. At the time, the decision was fiercely criticised by many economists inside and outside government, including subsequently by the National Audit Office, as a waste of public resources.[34] An industry task force had projected that, given continued investment, it might by 2020 be possible to reduce costs to £100/MWh – still expensive. However, offshore wind was the only conceivable way of meeting ambitious targets agreed under the European Renewable Energy Directive – which were legally binding under EU law, and backed by penalties for non-compliance. Initially also supported by the public 'Green Investment Bank', the government maintained support but moved to competitive auctions which over three successive rounds yielded prices at about £120, £60 and finally, in 2019, £40/MWh – a level no one had come even close to predicting, similar to the price of wholesale electricity. Between 2017 and 2019, around 95% of all newly contracted renewables capacity was offshore wind. Under the CfDs, renewables contracted at this price are effectively subsidy-free (especially given the carbon price also included in the EMR reforms), and as wholesale electricity prices have risen, due to escalating gas and carbon prices, the contracts are starting to generate income to the government, effectively 'subsidy-negative'.

In 2019, the government and offshore wind industry agreed the Offshore Wind Sector Deal, guaranteeing CfD auction rounds every two years to achieve at least 30 GW of deployment to 2030. In 2020, the new prime minister increased the ambition to 40 GW, along with measures such as local content requirements and an aim to treble the size of the UK offshore wind workforce (with supporting initiatives).

These developments provided sufficient confidence for the industry to invest at scale in growth and innovation. This generated economies of scale in local manufacturing capacity, the size of the turbines, and the number of turbines in a single project; investment in developing specialist support technologies (such as bespoke installation and maintenance vessels) and workforces and skills (both of which were previously repurposed from the oil and gas industry); and other improvements and efficiencies produced by continued learning-by-doing. The stable long-term support regime, coupled with increasing project size and accumulating experience, also attracted a wider range of investors, further reducing the cost of finance. Throughout – except for a political pause from 2015 to 2017 – these instruments were supported by both high-level, long-term commitments to the technology, and by more granular enabling measures to address specific barriers to development and diffusion.

[xiv] See Carbon Trust (2006)[138], Policy frameworks for renewables: Analysis on policy frameworks to drive future investment in near and long-term renewable power in the UK (www.carbontrust.co.uk). After the policy reform, offshore wind received two RO Certificates per unit of generation for 20 years following accreditation.
[xv] The Crown Estate is an independent commercial business created by Act of Parliament to manage the Estate of the British Crown, including the UK's territorial waters. This was the third and largest such auction for offshore wind developments.
[xvi] CfD contracts were organised as a certain volume of new renewable capacity sought in 'rounds', to which eligible renewable generators applied to receive a fixed 'strike price' for 15 years of generation capacity. If the market price for electricity falls below the strike price, the government pays the difference. If the market price exceeds the strike price, the generator pays the government the difference.

Wind energy: prospects and lessons

These cases demonstrate the varied, important and complementary roles of different types of public policy and public institutions in driving the development and emergence of wind energy, onshore and offshore. It underlines the evolutionary nature of these technologies and associated industries. As indicated in **Figure 3**, wind energy has continued to expand steadily – moving from the margins to a mainstream industry, along with declining global average costs (confounding arguments that the costs would increase as the best sites were used up). The IEA expects annual deployment to continue at least at 2020 levels (around 65 GW, nearly the total electricity generation capacity of the UK) to 2025, accelerating to around 90 GW per year with supportive policy environments tackling largely non-cost barriers, such as permitting, grid integration and social acceptance.

To a large degree, the success of wind energy has confounded CBA. The origins of the support programmes in the 1980s and 90s were political, driven by environmental concerns and exaggerated fears of global oil crises. The Brazilian programme was prompted by an electricity crisis, and used a targeted mix of policies unlike the classical economic 'least cost' prescriptions.
The UK programme was launched in the context of climate change concerns that became embodied in binding targets, domestically and internationally, which proved strong enough to withstand assault by those arguing that offshore wind in particular could never be economic.

All such forecasts hugely underestimated the potential for the cost reductions that emerged. Had standard CBA methods for policy appraisal dominated, such technological improvements would likely not have been predicted, the benefit would not have been foreseen and programmes would have been prevented, curtailed or abandoned. Instead, wind is now a mainstay of a cleaner and more diverse electricity system, and a major domestic industry in both regions. In 2020, globally, wind energy attracted more investment than any other power source.[35]

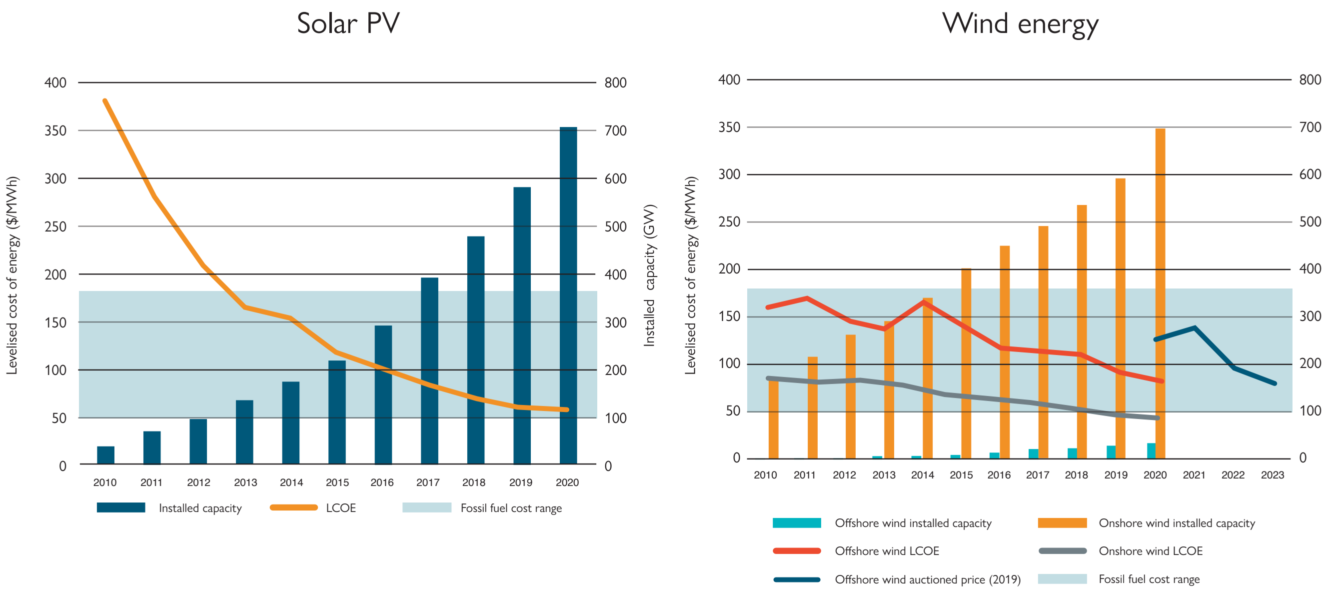


Figure 3: Evolution of capacity and cost of (a) wind, on- and offshore, and (b) solar PV, 2010–2020
Source: IRENA (2021) [32], with fossil fuel LCOE indicated as shaded blue at USD 50-177/MWh (p. 12 note 4).

2.2. Solar photovoltaics in Germany and China[xvii]

Solar energy is, almost by definition, the world's biggest renewable energy resource by far, with energy arriving at the world's surface at about 6,000 times the rate of humanity's energy use.

More than a hundred years after scientists first discovered the 'photovoltaic effect', its first key energy application was for the Vanguard space satellite, in 1958. After the 1970s energy crisis, governments put hundreds of millions of dollars into solar R&D, but many cut back on this as oil prices fell. In 1995, solar PV still cost about 0.5-1 €/kWh, at least 10 times the cost of conventional electricity production, and only a few hundred MW had been deployed globally – comparable to one single conventional power station – mostly for remote applications. PV contributed an estimated 0.003% of European electricity supplies.[36, xviii]

By 2020, just a quarter of a century later – about half the typical design lifetime of a coal power station – global installed capacity exceeded 700 GW – catching up with wind energy despite much later expansion (**Figure 3**). This is more than ten times what had been expected to be achieved by 2020 just fifteen years earlier. In contrast with the 2010 projection of the IEA World Energy Outlook, that "PV is projected to increase very rapidly, though its share of global generation only reaches 2% in 2035", the contribution of solar PV in Europe had, between 2010 and 2020, expanded by more than a factor of 1,000, to 5% of European electricity generation, beating the most optimistic of the mid-1990s projections of capacity by a full decade. In China, the change was even more dramatic.

The global contribution to date remains modest, but could transform electricity within a decade or two if the rates of exponential growth observed over the past decade – close to a doubling every two years - are sustained.[37,38]

In 1995, a US Interlaboratory Study had projected that costs might fall by a factor of two or three by 2030, or somewhat more with intensified R&D – maybe just enough to become competitive in sunny regions.[xix] The industry emphasised instead the need for scale. Throughout the 2000s and beyond however, most economic assessments rejected supports for solar *deployment* as a waste of public money. As late as 2014, to underline its view of the foolishness of European climate policy, *The Economist* described solar as the most expensive way of cutting emissions available[1].

Just six years later, in 2020 the IEA described PV as offering 'the cheapest electricity in history'.[39] In volume and cost reductions, PV's development has exceeded the wildest expectations, and transformed the global prospects for low-carbon development, demolishing most economic forecasts of the associated costs in the process. Yet it has in fact conformed to expectations resulting from 'experience curve' analysis.[40]

How did it happen, and what does this say about decision-making processes and the modelling that supports it? The wider story is told in a book by Greg Nemet, *How solar energy became cheap*.[41] The case studies illustrated below, and expanded in Online Appendix 2, focus on the role of decision-making in the German Energiewende, the motor of the European developments, and the interactions with Chinese policy, industry and markets.

[xvii] Synthesis of case studies by Alex Clark (Oxford University, UK) and Zhu Songli (Energy Research Institute, Beijing). See Online Appendix 2.
[xviii]Data, and an overview of the state of the solar PV industry at the time, from Grubb and Vigotti (1997).[36]
[xix] As cited in Grubb and Vigotti, *Ibid*.

The origins of the Energiewende

Hardly the sunniest of countries, the origins of the German *Energiewende* lay in the rise of environmental politics during the 1980s, fuelled by the oil shocks, acid rain from sulphur emissions, and reinforced by the Chernobyl nuclear disaster of 1986. Feed-in-tariffs (FiTs) for renewable energy were introduced in the 1990s, building up to the Renewable Energy Act of 2000. Progress mostly with other renewables enabled ambition to be raised, in 2004, with technology-specific FiTs (against the mainstream economic advice for 'technology neutrality') to implement a target for renewables to produce 20% of electricity by 2010 – something it would be hard to conceive of without solar energy. Between 2004 and 2010, this single, mid-latitude country in Europe with barely 1% of the world's population (and a much lower share of the world's incident solar radiation), accounted for more than half of all solar PV installed globally, which over those seven years grew from under 3 GW to 40 GW.

The emphasis in these years was political and strategic – critics tended to say, symbolic – with little sign of CBA. As our case study notes, any attempt to quantify the costs and benefits would almost certainly have killed the programme: it was very expensive.[xx] Moreover, the cost of solar PV during this period did not fall to anything like the extent that protagonists hoped, staying relatively static between 2003 and 2009 – something which analysts attributed to the pressures of such rapid expansion on supply chains and the markets for silicon.

All the more surprising then, that in 2010 the government adopted what became known as the *Energiewende* inception documents, which effectively engaged the entire nation in a strategic drive for energy transformation. The political roots were not just environmental, but with wider social engagement. The increasingly prosperous renewable energy industries had grown in power (at its peak in 2013 the solar business alone employed 370,000 people), and citizens and local communities became energy producers, benefitting from high tariffs, while the costs were socialised more broadly through electricity prices. Analytically, the key documents offered an effort at cost-benefit evaluation, heavily reliant on extrapolation of the previously rising fossil fuel prices and emphasising the potential trade, industrial, diversity and other benefits beyond the purely economic.

A growing backlash from mainstream energy industries was effectively silenced by the Fukushima disaster in 2011. Rapid further expansion followed, in Germany and beyond under the impetus of highly ambitious renewable energy targets agreed across the EU, accompanied by an acceleration of the long-promised cost reductions as the industry and supply chains matured.

[xx] See, for example, the stern criticism of the German Council of Economic Experts on the efficiency and success of the German Energiewende, which suggests a policy failure: "However, the point of the steering goals is not altogether clear from an economic perspective, as these additional constraints only place an additional burden on the energy transition and make it unnecessarily more expensive."[139] They recommended that the EU-ETS be relied on solely to avoid market distortion by other policy instruments such as FiTs. See SBE (2016).[139]

The internationalisation of the industry, and locking-in ambition

A key element in the cost reduction stemmed from the other great change during the 2000s, later and less visible to the rest of the world, in China. As late as 2003, solar PV was mostly confined to a few small companies that used it to bring electricity access to remote areas of rural China, with modest government support; the total installed capacity was just 55 MW. In that same year however, researchers recently returned from Australia (when that country curtailed its solar R&D programme) founded Suntech, along with a few other small start-up companies, establishing the first batch of modernised PV manufacturing factories. Two years later, buoyed by the surging demand from Germany, these companies raised funds through international IPOs which fuelled rapid growth. In 2008, China became the world's top producer of solar panels.

This was, however, almost entirely for foreign markets; domestic solar capacity still amounted to a fraction of one big conventional power plant. China's own Renewable Energy Act of 2005 had focused more on wind, which was cheaper and involved much larger projects suitable for support under the Kyoto Protocol's Clean Development Mechanism. China risked being trapped in a 'both ends abroad' industry, with both technology and market heavily dependent on other countries. That vulnerability was exposed in the aftermath of the global financial crisis in 2009, which briefly stalled the global growth of solar PV.

Domestically, a first significant step towards deployment was a 2020 target for 15% renewable energy, announced as part of the Chinese 'Nationally Appropriate Mitigation Actions' offering to the 2009 Copenhagen climate change conference. But the financial crisis left deeper wounds in the West, and the plummeting price of Chinese PV became a point of major contention. Trade disputes ensued, with both the EU and US raising tariffs, with a potentially awkward compromise which underlined the challenges facing the international trade system in the face of policy-driven transformative changes.[xxi]

Faced with the risk of collapsing international demand stranding a burgeoning domestic manufacturing industry, China launched its own domestic programmes, with startling results. Learning from the European experience, fixed-price FiTs were established, with regular adjustments to chase the falling prices, along with other instruments. As late as 2008, the contribution of solar PV was negligible at just 300 MW, but grew by a factor of 20 within five years, to 6.5 GW by 2012. The target in China's 12th Five-Year Plan (FYP) (2011–2015), initially 5 GW, was repeatedly revised, with deployment by 2015 exceeding 40 GW. A similar story unfolded for the 13th FYP, with a goal of 110 GW being more than doubled by 2020, supported by increasingly sophisticated financing arrangements sometimes backed by the People's Bank of China 'green finance' policies, fuelling the ongoing but transformative impact of exponential growth.

Ultimately, and building upon the earlier more exploratory developments elsewhere, the German and Chinese solar PV developments interwove to create this extraordinary change. The German commitment – a broad social, industrial and financial commitment to new ways of generating electricity – helped to establish the industry at scale, in the face of most economic advice to the contrary. German demand, more than any other, created the lure for Chinese manufacturing to develop and underpinned its ability to secure international finance, bringing costs down radically. Once established, the Chinese industry became an important factor raising the credibility and ambition of renewable energy in China itself, and spearheading the globalisation of solar PV from which the entire world now stands to benefit. Neither country significantly delayed their deployment programmes on the basis of relative costs and benefits; rather, they pursued opportunities based on their respective strengths.

[xxi] The trade system being designed on classical traditional economic assumptions about comparative advantage in the face of transformational dynamics driven by policy and consumers in one country (e.g. Germany), but with others (e.g. China) rapidly moving to reap the benefits. For an account of the EU-China PV trade dispute, see Voituriez and Wang (2015).[140]

Uncertainty and forecasting

One other important lesson concerns the limits of forecasting. Had either country tried to apply CBA, they almost certainly would have got it wildly wrong.[xxii] **Figure 4(a)** shows the historical trend of the costs of solar PV electricity, compared against forecasts as projected by the IEA, and as represented in successive IAMs typically used to assess the cost of emissions mitigation. Inset is the annual cost improvement ratio assumed in the model projections from 2014, compared to that actually realised. Even more striking, **Figure 4(b)** shows the trend of observed capacity cost, along with (the blue lines) previous assumptions about the 'floor price' of PV – written in to many models on the assumption that solar PV, due in part to 'balance of system' (i.e. non-module) costs, could not go below a certain level.

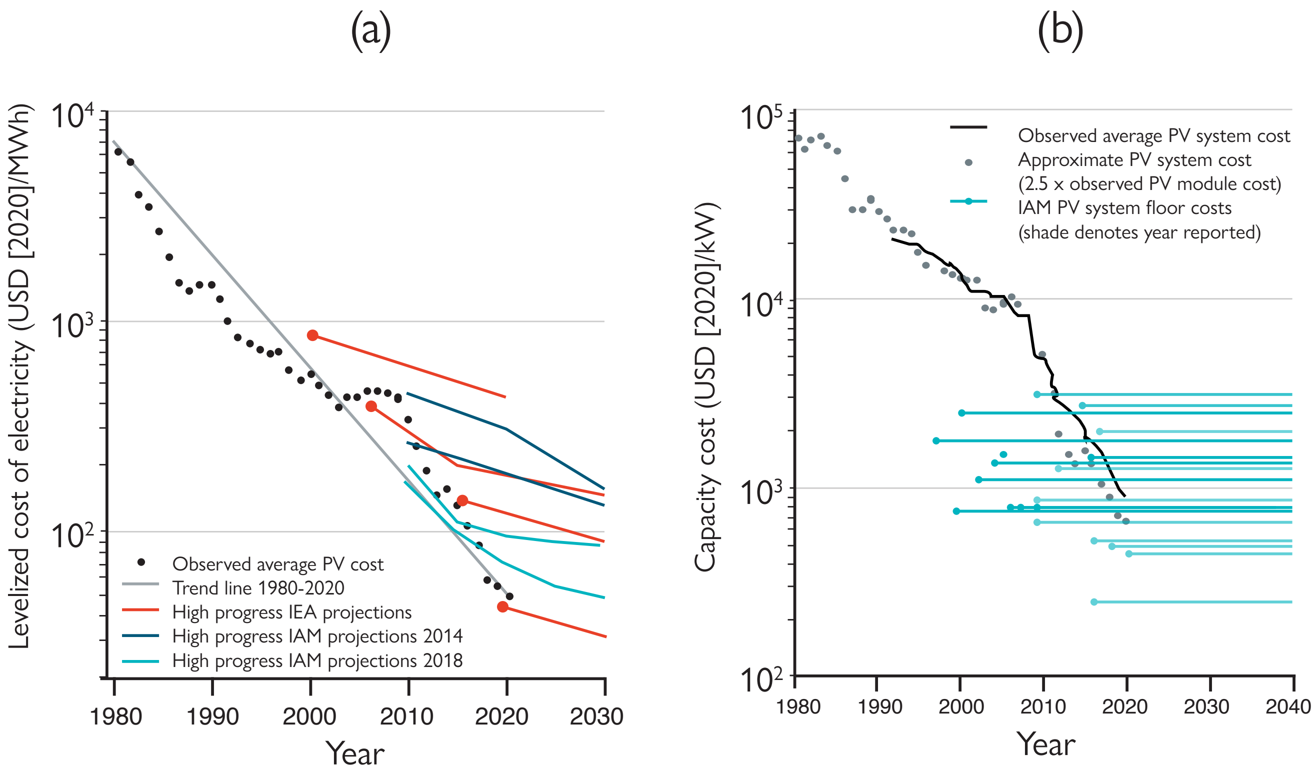


Figure 4: Solar PV cost of energy and capacity costs: forecasts and outturn
Notes: A. The black dots show the observed global levelized cost of electricity (LCOE) over time. Red lines are LCOE projections reported by the IEA, dark blue lines are integrated assessment model (IAM) LCOE projections reported in 2014 and light blue lines are IAM projections reported in 2018. IAM projections are rooted in 2010 despite being produced in later years. The projections shown are exclusively 'high technological progress' cost trajectories drawn from the most aggressive mitigation scenarios, corresponding to the biggest projected cost reductions used in these models. Other projections made were even more pessimistic about future solar PV costs. B. Solar PV system floor costs implemented in a wide range of IAMs. The colours denote the year the floor cost was reported, ranging from 1997 to 2020. Observed solar PV system costs are also shown. Source: Way et al. (2021).[40]

All these forecasts were wildly and persistently wrong. Had they been fed into CBA, they would undoubtedly have indicated the programmes should be cancelled. The only approach to forecasting which has proved more consistent to date has been based on 'experience curve' extrapolation of the past relationship between cumulative capacity and cost, which in work elsewhere is now being applied to offer probabilistic forecasts of the range of continuing cost reductions which could be reasonably expected on this basis.[40]

[xxii] Some researchers pointed to the potential for cost reductions, using the approach of experience curves discussed in the next section, to argue that solar PV could become much cheaper given sufficient investment.[42] There were still sizeable uncertainties – such forecasts remained contingent not only on learning parameters, but on global investment continuing its exponential trajectory – on which there was little agreement.

Conclusion

The solar revolution – for a revolution it is, by almost any standard – underlines key themes crucial to the question of how governments evaluate low-carbon policy. First, innovation is evolutionary – building from early R&D through successive waves of market-based innovation, expansion and cost reduction. Correspondingly, it is cumulative – as also now clearly revealed in patent analysis[24] – with progress building on the shoulders of earlier efforts, experimentation and learning, as well as supportive systems. Third, in the short-run it embodies considerable risks and uncertainties, as viewed by actors at the time; the future is uncertain, but a CBA rooted in present-cost assumptions or even expert projections will very likely mislead. At best, it might have shifted emphasis away from the FITs which fuelled growth of the existing silicon solar cell industry, to R&D on alternative solar technologies. One can never know (though the alternatives were hardly starved of investment), but this might well have slowed down the evolutionary development of an industry which is already now providing cheaper as well as cleaner electricity to more and more countries.

The cumulative nature of the progress seems to find expression in the simple metric of the 'experience curve' relationship between volume and cost reduction, which with hindsight, and allowing for the inevitable fluctuations, solar PV seems to have followed closely (according with past cost forecasts made using experience curves[42]). Consequently, fourth, a policy-driven transformation requires political commitment to stay the course, ideally rooted in legislated targets to support investor confidence.

A final lesson revealed from the PV experience, perhaps even more than for wind, is the internationally interactive nature of any major transitions. As charted in Nemet (2019)[41] the roots of solar PV lie in R&D led in the US, Japan and Australia, but none of these ended up driving its commercialisation. It was the interaction of German determination, embedded and extended in a pan-European context, interacting with Chinese industrial and policy entrepreneurship which finally delivered PV as a foundation for 21st century decarbonisation. Moving production to lower cost producers is, in fact, an essential part of any global transition. While the shift of production from Germany to China has been a loss to German production – though many retain a large stake in the value chain – in the longer term it is a boon to consumers in Germany, Europe and the world.

2.3. Energy-efficient lighting in India[xxiii]

Access to electricity in India has grown rapidly in recent decades, with the proportion of households using electricity for lighting increasing from 35% in 1990 to 99% in 2020.

To minimise electricity bills and reduce the need for additional electricity generation capacity (and their attendant CO_2 emissions), the Indian government introduced a series of policies to encourage the uptake of energy-efficient lighting – particularly for low-income households.

The first key scheme, launched in 2008/9, was '*Bachat Lamp Yojana*' (Energy Saving Light Scheme). This voluntary scheme sought to replace inefficient incandescent bulbs in households with more efficient – but more expensive – compact fluorescent lamps (CFLs). Under this scheme, private investors procured CFLs which were then distributed by electricity distribution companies to households in exchange for old incandescent bulbs. Procured from high-income countries under the terms of the Kyoto Protocol's Clean Development Mechanism (CDM), the savings then generated Certified Emission Reduction credits for the electricity distributors and investors based on the CO_2 emissions saved. The value of these certificates enabled the CFLs to be distributed at the same price as traditional bulbs. About 29 million CFL bulbs were distributed in this way, resulting in over 400 MW of avoided electricity generation capacity.

After a few years, the reducing market value for such CDM emission reduction credits and increasing cost of raw materials for CFLs, saw investors withdraw, but it laid the foundations of interest and capability. In January 2015, the Indian government launched the UJALA ('Unnat Jyoti by Affordable LEDs for All') scheme, with an aim to provide highly-efficient, yet again relatively expensive LED lamps to low-income domestic consumers for an affordable price. The core element of the programme was the bulk public procurement of LEDs through Energy Efficiency Services Limited (EESL), a public sector joint venture established to act as a coordination body, allowing economies of scale to achieve the lowest price possible. LED bulbs were then sold at registered kiosks with a minimal purchase price, with the remaining cost of procurement recovered to EESL through instalments on electricity bills. The UJALA scheme has been instrumental in transforming the efficiency of lighting in Indian households, with 90% of electrified households in India using LED lighting. Annual sales of LED bulbs in India rose from 3m in 2012 to 670m in 2018[43], with prices reducing from INR 800 in 2010, to just INR 70 in 2019.[44, xxiv] Estimates suggest that LEDs distributed under the UJALA scheme alone has so far induced at least 47 TWh in energy savings, a significant contribution within wider Indian programmes on energy efficiency which overall are estimated to have saved well over 100 $MtCO_2$ emissions.[45]

However, due to a lack of a domestic manufacturing industry, much of India's fast-growing demand was met by relatively low-quality bulbs produced in China rather than through domestic supply chains. Following this realisation, in 2015 the Indian government announced that public procurement of LEDs must have some domestic value-added component. This led to the rapid development of a domestic industry in downstream LED manufacturing (i.e. assembly of the final product), growing from negligible levels in 2010 to a sector with a market value of more than US$1bn by 2019. In 2021, this was supported by further measures to incentivise the production of LED components, as well as their final assembly.

Both of these key schemes emerged as a result of extensive consultation processes with investors, government departments, lighting distribution companies and consumers, driven by strategic objectives of maintaining energy affordability and supply in the face of rapidly expanding access to electricity.

[xxiii] Drawn from case study of Indian LEDs led by Kamna Waghray, The Energy and Resources Institute (Online Appendix 3).

[xxiv] Although this should be seen in the context of substantial cost reductions delivered through global developments in LED technology, as examined by Weinold et al. (2021).[141]

Mixed legacies

There is no clear evidence as to whether this transformation was, or could have been, supported by a formal cost-benefit appraisal. Such assessment could only have yielded positive results if it had far-sighted insight into the cost reductions that transpired. In practice these were secured through bulk purchase, competitive auctions and smart polices at the distribution level, underpinned by the national strategic commitment. It is clear that its precursor, Bachat Lamp Yojana, was supported largely through the international Kyoto Clean Development Mechanism, but then laid the foundations for its far more ambitious and far-reaching successor.[45] The evolutionary nature of innovation, and the impossibility of foreseeing all the benefits that may flow, again comes through as an important lesson.

Nevertheless, these programmes could not address the issues such as a lack of domestic R&D, suitable infrastructure and limited access to technology due to restrictive intellectual property rules, that would have allowed a full-chain domestic LED manufacturing industry and supply chain to flourish. India remains heavily dependent on imports for LED chips. However, the setting of industry standards facilitated a manufacturing industry for LED-based products (LED luminaires, LED driver circuits). Domestic LED manufacturing capacity grew to 176 manufacturing factories and more than 300 registered companies, with a present market value new exceeding US$1bn[46,47], increasingly driven by now markets including automobiles and signalling.

3. Economic and policy dimensions of technological transitions

The developments outlined have transformed the prospects for global emissions reduction and created huge value.

In 2020, investment in wind and solar PV amounted to around $150bn each, together accounting for over 35% of total global electricity generation investment.[35] Compared to miniscule contributions a decade earlier, together they were already displacing around 10% of global power sector CO_2 emissions, leading the IEA to tear up its previous forecasts. The transition to efficient lighting has contributed to declining electricity demand in many developed countries, and the Indian LED programme has help to connect hundreds of millions of people to affordable modern energy services, while reducing the need for further electricity capacity additions.

The decisions which led to these developments were driven primarily by strategic and political factors. To judge from the estimates, projections and common pronouncements on solar PV and wind a decade earlier, formalised CBA based on trying to monetise the costs and benefits on the basis of marginal, 'equilibrium' welfare economics would probably have killed these programmes. If nothing else this illustrates the risk of pessimism bias, already explained in section 2, if CBA is applied to challenges of radical innovation. For the low-carbon transition, we need better tools of policy appraisal.

In practice, the case studies illustrate much more. This section outlines key characteristics of innovation and transition they reveal, and the key concepts and insights from related theories, as the key context for an evaluation approach more suited to the task.

3.1. General characteristics

We start by observing some key characteristics of the case studies summarised in section 2. These include:

- **Cumulative progress.** In all these cases, success was built upon previous progress. In technical terms, the process was *cumulative*, and *path-dependent*.
- **Market-based innovation.** Much of the progress during the past few decades involved market-based innovation and cost reduction, particularly associated with the deployment phase of **Figure 1**.
- **Sustained and targeted support for deployment.** Correspondingly, the progress involved sustained support through targeted public policy for demonstration and deployment of key technologies, in most cases for 1–2 decades beyond the period dominated by public R&D, with 'market-correcting' instruments such as carbon pricing playing a limited role, at best.
- **Deep uncertainties,** at least in the earlier stages of deployment as perceived *ex ante*, until critical thresholds were passed.
- **Strong international dimensions.** It was indeed internationalisation that often sustained the growth of the technologies and helped them pass critical thresholds.

Cost reductions can be presented in relation not only to time (e.g. **Figure 4**) but also cumulative capacity (**Figure 5**). The latter is now well charted in terms of 'experience curves' – a cost reduction associated with each doubling of installed capacity. Initial stages, which may explore different approaches before a dominant design emerges, may see greater variation (as illustrated with the solar thermal data in red), Beyond this however, literature generally finds a relatively stable ratio – sometimes called the 'learning rate' or 'progress ratio' – implying a straight line when plotted logarithmically, as illustrated. Such relationships have been estimated for hundreds of technologies, finding systematic variations between different types technologies as discussed below. As noted, Meng et al. (2021)[25] find that cost forecasts based on such relationships seem to have been more accurate than expert-based judgements, and some analyses now use experience curves are to make probabilistic projections of future cost trends.[48,49]

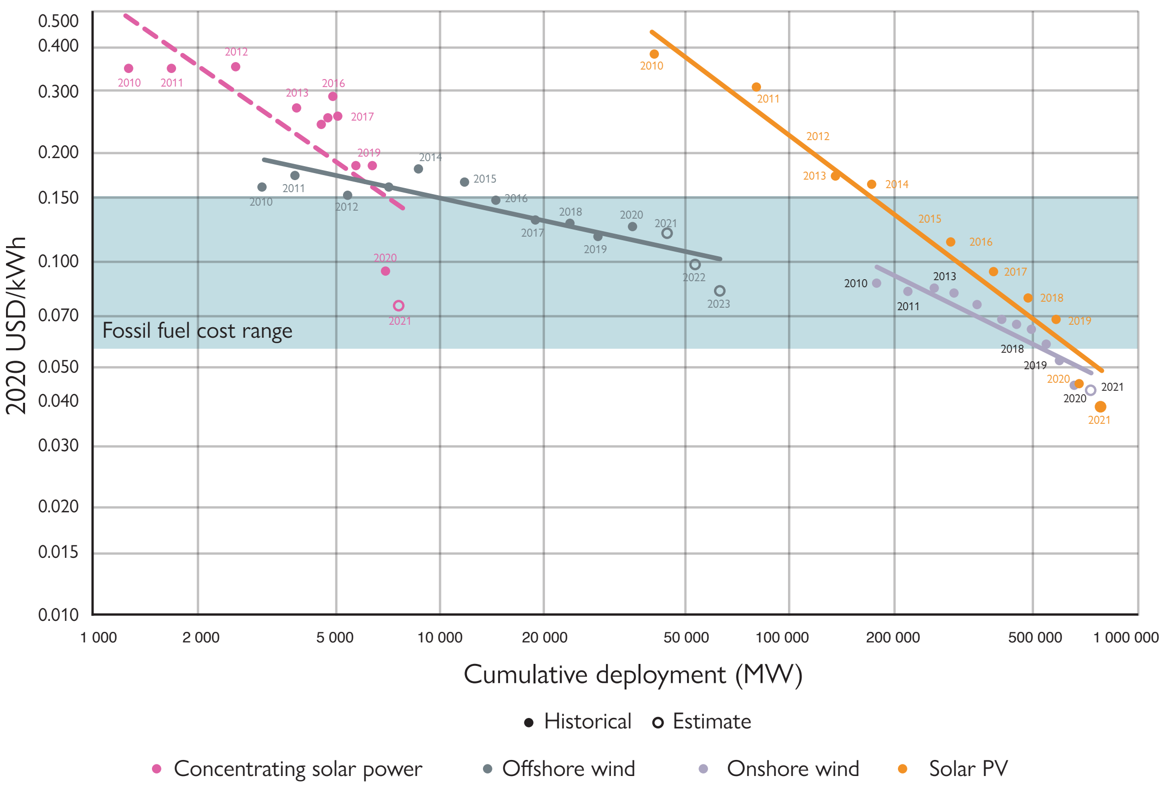


Figure 5: Experience curves for wind and solar energy to 2020 and current contracts
Source: IRENA (2021)[32], Figure 1.9. This includes the most recent data as of mid-2021, including forward contracts. Note the logarithmic axes on both scales.

Experience curves measure a correlation. Since innovation has multiple internal and external (spillover) drivers, causality is bidirectional, as declining costs would also stimulate diffusion. However multiple lines of evidence demonstrate strong causality from scale to cost reductions, particularly in the emergence phases of *active deployment*. The distinction between deployment and diffusion may be best understood as the point at which the dominant causality shifts into the stage of self-sustaining market increases, with positive feedbacks which continue cost reductions.[24]

In each of our three case studies, the policies most critical to success acted directly to strengthen the positive (reinforcing) feedbacks of technology development and diffusion. Public procurement of efficient lightbulbs in India, subsidies for the deployment of solar PV in Germany, and concessional public lending for wind power in Brazil were all forms of targeted investment and market creation for key technologies. Investment led to technological improvement, falling costs, rising demand and more investment. Given the dynamics of innovation, it is not surprising that the policies that have proved to be most effective in launching transitions have been those involving targeted investment and market creation for the desired new technologies.

The result is that the processes have been inherently evolutionary, and yet contingent upon key points of intervention and internationalisation. This was evident in wind (initial support in Europe and California, with globalisation after the financial crisis including Brazilian industry, and pan-European continuity for offshore wind deployment in the mid-2010s) and solar PV (the continued expansion of the German programme combined with shift of manufacturing to China, bringing down global costs and prompting its own domestic programmes). Even India's LED programme built upon the precursor *Bachat Lamp Yojana* programme for compact fluorescent bulbs, supported by the Kyoto Clean Development Mechanism, from which India could proceed to use the bulk purchasing power of the state combined with competitive auctioning to push through its own cost revolution for LEDs.

The typical dynamics of transition are illustrated in **Figure 6**. The top panel illustrates a classic 'bell curve' of adoption, led by innovators and early adopters, with the bulk markets then following as a technology becomes mainstreamed, generally with a tail of late adopters. Translated into market share (lower panel) the overall dynamics of transition generally occur as an S-curve (technically, sigmoid or logistic transition): an initially slow process of emergence that then involves exponentially increasing deployment into a phase of rapid growth, as a technology breaks through into mainstream market diffusion, before finally culminating and stabilising as the entire industry matures. The technology penetration may reach different levels, depending in part upon the extent to which the entire industry and market structure is reconfigured. Maturation might, for example, involve coupling of previously disparate sectors (such as electricity generation and road transport).

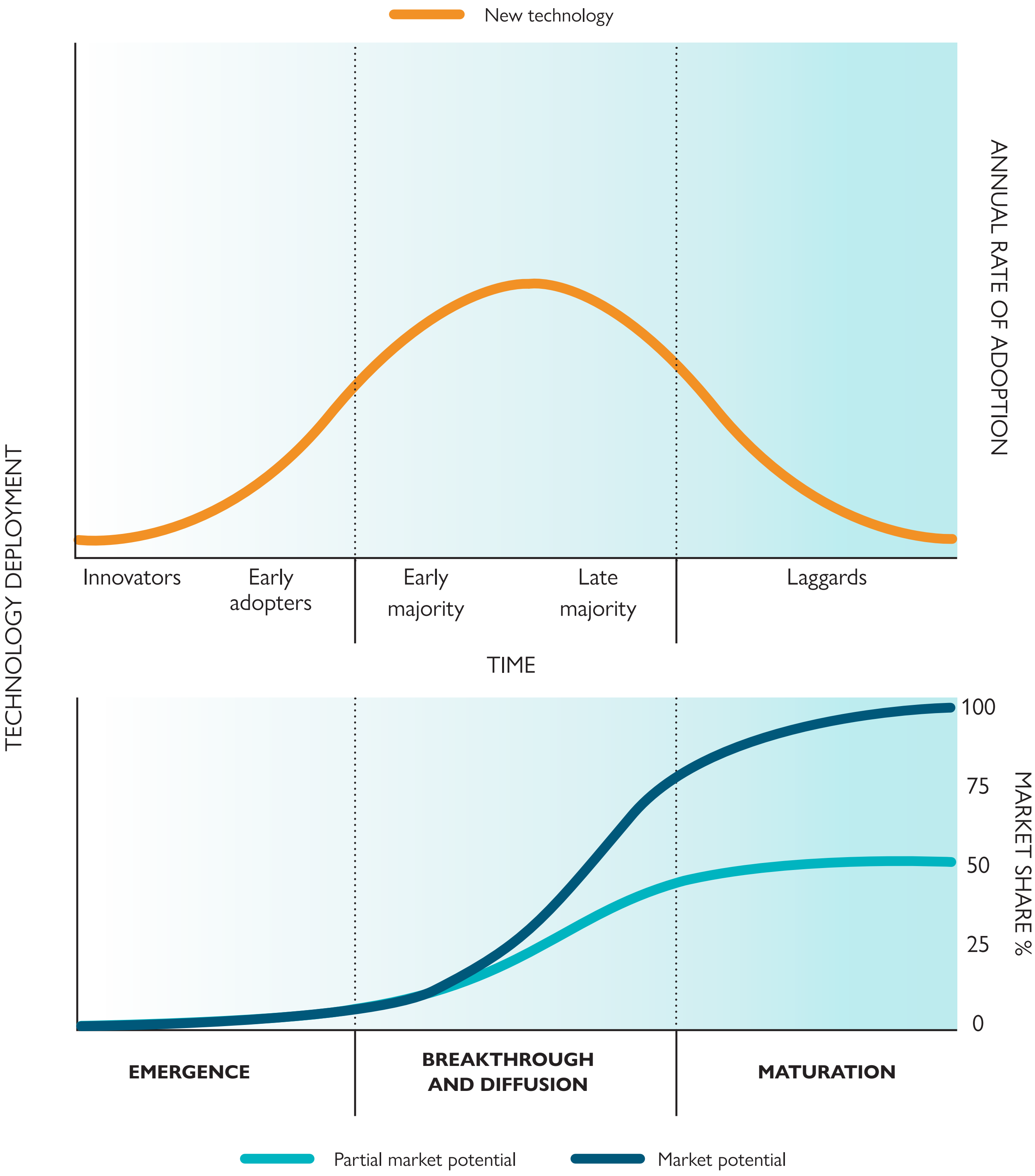


Figure 6: Typical S-curve dynamic of technology transition

A substantial body of evidence suggests this pattern, first observed in natural population dynamics, appears to hold across a wide range of technologies, across sectors and geographies – particularly when examining the growth in market share of new technologies (e.g. Fisher and Pry, 1971; Marchetti and Nakicenovic, 1979; Rogers, 2003; Grubler, 1996[50–53]). However the timescale to emergence, and the subsequent rate of growth, varies substantially[54] – and these are factors which have a strong bearing upon the overall economics, and which policy has influenced enormously. At a global scale, the three technologies of our case studies – particularly wind and solar PV – have barely yet left the zone of emergence, and are growing at exponential rates, but as noted above may take another decade or two before they replace incumbent technologies at scale in many countries.[34,35]

3.2. Theories of innovation

In parallel with these developments, recent decades have seen substantial advances in our understanding of how and why processes occur (though, like many things, the precursors have existed for much longer, including in the writings of leading economists Schumpeter and Polanyi, in the inter-war years).

A burgeoning literature has generated insights into two, complementary perspectives concerning *technology innovation* and the key social, economic and institutional processes that occur during major *socio-technical transitions* (see section 4.3). Although these literatures emerged independently, they are highly complementary, and have become increasingly interconnected over time.[55]

Since Schumpeter developed the initial conception of the technology innovation chain in the early 20th century – a linear process formed of three successive stages; invention, innovation, and diffusion – the concept has developed a great deal, resulting in the insights described in section 2.3, and illustrated in **Figure 1**. A core development has been to move away from this *linear* conception of technology innovation, with a narrow view of the processes involved and implying a limited role for public policy (proving R&D funding and correcting 'market failures'), to that of a *technology innovation system (TIS)*; an altogether more complex notion.

The literature on TISs focuses on the granular, 'bottom-up' perspective of the drivers, barriers and dynamics concerning the development and adoption of a particular technology. The original definition of a TIS comprised a "network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure and involved in the generation, diffusion and utilization of a technology".[56] Following this, a TIS has three core 'components': 1. Actors; including technology developers, intermediaries, users, financers and regulators; 2. Institutions; structures that set and form 'the rules of the game' comprising laws and regulations, social and technical norms, and shared expectations; and 3. Technology and infrastructures; including characteristics such as costs, reliability, safety, usability, reparability, modularity and compatibility of technological artefacts and the wider technological infrastructure in which they sit.

These together influence functions of the innovation system: key structures that must be in place (or 'fulfilled') in order for the technology in question to fully develop and diffuse into the market.[xxv] For the emergence of technologies to tackle societal or public good problems, developments across these multiple, largely interdependent functions have often been induced through a few particularly important motors of change that trigger virtuous circles. Notably, governments can help to guide the search by identifying key problems and establishing goals to tackle them. This encourages mobilisation of resources, knowledge development and growing legitimacy, which in turn helps align and strengthen expectations for the technology, and the formation of protected market niches to kick-start virtuous circles of positive learning, cost reduction, and enhanced legitimacy.[57] Various indicators may be used to assess the extent to which these functions are in place and fulfilled, and thus where policy should be introduced or revised to tackle shortcomings.[xxvi]

[xxv] Various specific (but similar) sets of TIS functions have been identified over time (e.g. Bergek et al. 2008; Chaminade and Edquist 2005; Hekkert et al. 2007[142–144]), but one of the most common conceptions details a list of seven functions: 1. Entrepreneurial activities; 2. Knowledge development; 3. Knowledge diffusion through networks; 4. Guidance of the search; 5. Market formation; 6. Resource mobilisation; creation of legitimacy.[57]

[xxvi] Hekkert et al. (2007)[144] list examples of such indicators for each function. For example, 'entrepreneurial activities' may be measured though the number of new entrants to a market or the number of diversification activities by incumbent actors, while 'knowledge diffusion through networks' may be measured through mapping the number and size of workshops and conferences devoted to the technology in question over time.

3.3. Theories of transition

Beyond technology innovation per se, a complementary literature has developed more 'top-down' insights into the wider processes of socio-technical transition.

This encompasses the dynamics through which a range of different and often competing technologies in a given system (at different stages of development and maturity) may achieve widespread diffusion and potential dominance in the market, remain dominant, lose dominance, or fail to achieve widespread diffusion in the first place. In particular, these approaches highlight different processes that tend to dominate at different scales. One of the most widely adopted is the 'Multi-Level Perspective' (MLP), which identifies interactions between three main levels.[58,59]

The core ('meso') level is the socio-technical 'regime'. This comprises the deep structure of semi-coherent rules in culture, politics, institutions, markets, industry and technology that coordinate and configure activities and expectations. The components of generation and transmission, organisation, regulation, and governance of electricity systems is a highly relevant example. Such regimes are conceived as internally stable and self-reinforcing – the existing infrastructure, combined with familiar rules and procedures, facilitate investment, but also creates 'lock-in', with innovation by default occurring only incrementally.[58,60]

The two remaining levels are usually defined in relation to the socio-technical regime. The 'niche' ('micro' level), provides 'incubation' spaces where new technologies or practices that sit outside the current practice and dominant regime can emerge, protected from 'normal' market pressures.[xxvii] Niches gain momentum and are more likely to be successful in leading to widespread adoption if the new technology aligns well with the existing regime, if expectations become more precise and more broadly accepted, if various learning processes results in a dominant design, and if actor networks and supportive coalitions continue to grow to include powerful actors in the existing socio-economic regime.[55,58,60–62] In turn, this may well involve pressures from 'above' the existing regime, or the 'landscape' ('macro' level), including factors such as demographical trends, political ideologies, societal values, and macroeconomic patterns, which usually change slowly but can also exert shocks to the system, such as through energy crises or pandemics.

The interaction between these three levels can lead to different pathways of transition, but all share the underlying characteristics of potential for highly non-linear change which may well lead to wider transformations – the move from horses to cars being a classic example (**Box 4**). This process leads to outcomes which are generally hard if not impossible to accurately predict, and may vary or occur at different paces in different national contexts.[xxviii]

[xxvii] Niche development allows three broad processes to occur with respect to the new technology or practice: 1. the articulation and adjustment of expectations and vision for innovation activities; 2.the construction of actor networks and coalitions, and 3. various forms of learning (including learning-by-doing, learning-by-using and learning-by-interacting).

[xxviii] Geels and Schot (2007)[145] conceived a typology of five pathways: 1. Reproduction (where there is no pressure upon the regime, which remains dynamically stable and continues to reproduce itself in a path-dependent manner); 2. Transformation (where there is moderate landscape pressure at a time where niche innovations are insufficiently developed to create a new regime, and current regime actors instead modify the existing regime); 3. De-alignment and re-alignment (where landscape pressure on the regime is substantial and sudden, destabilising the existing regime but with no sufficiently mature niche to produce an immediate substitute. Multiple niches compete, with one becoming dominant over time, forming the new regime); 4. Substitution (where landscape pressure on the regime is substantial and sudden, and opens a window for a mature niche innovation to form a new and replace the existing regime); and 5. Reconfiguration (where niches are adopted into the existing regime to serve localised demand, but which subsequently trigger further adjustments in the fundamental architecture of the regime). Subsequent work has since sought to elaborate upon these basic pathways, with sub-categories and other conceptual possibilities.[145,146]

BOX 4:

A ‘classical’ transition: from horses to cars

One dramatic illustration of how socio-technical transitions unfold is the shift from horse-drawn carriages to automobiles in the US.[xxix] Automobiles emerged in the 1880s and 1890s, when pioneers added steam engines, electric motors and internal combustion engines to carriages and tricycles. These early cars were heavy, fragile and slow, and they frequently broke down. They were expensive ‘toys for the rich’ that were used in small application niches, such as promenading in parks and on boulevards and in racing. These application niches stimulated initial learning and improvements. The broader landscape development of an expanding middle class, with more money and free time for sport and leisure established the popularity of automobile racing and touring, leading to rapidly growing sales of gasoline vehicles (while sales of electric and steam-powered vehicles stagnated). In the early 1900s, gasoline cars began to be used for more practical purposes by travelling salesmen and doctors. These growing niches stimulated the search for cheap, sturdy cars which, culminating in 1908 with Henry Ford’s Model T.

Early cars faced social acceptance problems, because speeding on unpaved roads killed people and livestock, and created dust waves that hindered pedestrians and wagon drivers. In response, policymakers started regulatory processes, introducing speed limits, traffic rules, car registration, driving schools and licensing. Policymakers also funded more road pavements to make urban environments more suitable for cars.

While these policies created an increasingly supportive environment for cars, various landscape developments began to create a more hostile environment for the focus of the incumbent regime – horses. Urban expansion lengthened travel times and increased road congestion in narrow streets; the sanitary movement heightened medical and cultural concerns about horse excrement in streets; and horse-tram and -bus companies faced high operating costs related to stabling and feeding thousands of horses.

Mass production and further incremental improvements reduced the cost of a car by more than half between 1908 and 1916, facilitating even more widespread adoption. Road infrastructures were further expanded and highways, were built in and around cities, coordinated in part by the new federal Bureau of Public Roads, and supported by an increasingly powerful lobby of highway engineers, suppliers (e.g. cement and asphalt, construction firms), urban planners, and automobile clubs. Educational campaigns taught children and pedestrians new routines for crossing roads, and public perception of a road’s function changed from a social meeting place to a transport artery.

Between 1910 and 1940, cars grew from small niches to dominating the ‘vehicle’ market. Complete reconfiguration followed the Second World War, when lower costs and higher incomes entrenched the new car regime socially, economically and infrastructurally. From 1956 to 1992 the Interstate Highway System was created with over $450bn of federal funding (in today’s prices). A car culture emerged as automobiles were embedded in daily routines: commuting between suburban homes and down-town jobs; shopping malls on the edge of cities, reachable only by car; holidays with cars leading to campgrounds and motels; and people could relax in drive-in cinemas and eat in drive-in restaurants. The car industry, including its supply chains, became a crucial economic sector, with innumerable linkages including the petroleum industry and public works. This ensured the complete triumph of cars over mass transit alternatives and firmly established automobiles as the dominant regime in the US transport system.

[xxix] This example is drawn from a summary presented by Victor, Geels and Sharpe (2019)[147], drawing on more detailed analysis by Geels (2005).[148]

3.4. Theoretical underpinnings – dynamics and uncertainty in complex systems

The qualitative approaches outlined on innovation systems and transition dynamics are associated with economic perspectives quite distinct from the classical framing of equilibrium economics and marginal changes.

Consciously or not, they relate more to other schools of economic thought, more associated with Keynesian, developmental, institutional and evolutionary economic theories. All these are grounded in views of economies as complex systems.

'Complexity science' is not generally considered an economic theory, but it informs views of economic systems which emphasise dynamics and uncertainty. The economy, as a complex system – and as illustrated by the qualitative theories of innovation and transition just outlined – is made up of many mutually interacting agents, subsystems, institutions, technologies and regulatory and political systems.[63–65] Complexity theory is the study of systems with interacting internal elements, and of the emergence of a macro structure stemming from these interactions. It results in an inherently dynamic view of systems, though with a sometimes subtle (and often misunderstood) relationship to equilibrium theories (**Box 5**).

Core to these theories is that diverse participants in the economy ('Agents') make decisions using plausibly available information. Decisions influence economic outcomes, which feedback to alter decisions. This sometimes leads the economy to periods of stability, but most of the time change leads to further change. The complex dynamics of change within the economy drive the emergence of phenomena such as bubbles and crashes, business cycles, technology transitions, and the constant creation of new business strategies, markets and institutions.[xxx]

[xxx] Steady states can arise, but are not assumed to necessarily happen – see Mercure et al. (2019)[149] for a classification of theory and methods.

BOX 5:

On equilibrium, complexity and modelling

An equilibrium in economics is a state in which no agent has incentive to change their behaviour, such that the economy will remain static until external factors change. If a stable equilibrium exists for a system, it still takes time to get there. Standard general-equilibrium (GE) theory focuses on conditions of equilibrium, and growth in terms of accumulated resources, rather than the dynamics of change. Equilibria may be local but not global, implying potential for instability if pushed beyond the 'local conditions'. Systems may have no equilibrium, or it is never reached because it takes longer to reach it than the time for the context to change. In the economy, inertia due to the long lifetimes of productive capital[157] and the connectivity of economic networks[158], impose such delays in reaching equilibrium.

In practice, there exist different timescales and length-scales over which non-equilibrium systems may exhibit properties closer or further away from equilibrium, or more or less volatile and uncertain. Some quantities can be predicted with relative ease for longer periods than others (e.g. employment in comparison to financial asset prices). It is consequently useful to reflect on the relationship between complexity science and equilibrium economics. Specifically, it is useful to dispense some common myths.

The first is the simplest: equilibrium theory does not assume that economic systems are simple, or 'not complex' in the ordinary meaning of the word. Indeed, several of the foundational texts emphasise that a key rationale for markets is the complexity of economic systems, with their millions or billions of individual decision-makers, technologies and resources. The 'magic' of neoclassical theory is the demonstration that decentralised decision-making by self-interested agents can, if conditions assure cost-reflective pricing, lead to an overall optimum use of resources in a steady-state. The political-economy arguments of Hayekian theories add that this preserves individual freedoms, in sharp contrast to the ethical and practical problems of central planning.

In contrast to complexity science however, equilibrium theories *are* simple in that they do not intrinsically embody the innovation and transition dynamics of major transformations. Somewhat paradoxically, this applies to the bulk of literatures on growth theory, which model growth based on the accumulation of resources (labour, capital etc.) and productivity gains are assumed to originate from processes external to the economy.

The second myth is that GE theory implies there is a long-term and unique optimal pathway for an economic system, based on rational foresight. In fact, in the mainstream economics literature, the mathematical elegance of its foundational Arrow-Debreu theory quickly became criticised *not* for its restrictive conditions, but for the opposite – its extreme permissiveness. The results of Sonnenschein, Mantel and Debreu in the early 1970s demonstrated that GE theory is in fact incredibly *unrestrictive*. Fundamental GE theory does not rule out multiple equilibria and absolutely does not imply that any given trajectory arising from unrestricted market forces results in a least-cost global optimum. Induced innovation and much that flows from it, including path dependence, is entirely consistent. The word 'general' in GE theory simply means balancing supply and demand across the economy. It has little predictive or constraining power (hence the title of a chapter on the SMD Theorem in one of the classical economics textbooks: *Anything Goes*[159]).

A major concern in modelling low-carbon economics is that fundamental GE theory has often been extrapolated to models which assume equilibria are global (not just local), and multi-period, with optimising actions taken at all points in time with (in any given run of such models) perfect foresight and perfect coordination across all actors, no transition costs and no other market failures. Such models take the underlying idea of GE and extrapolate it *ad absurdum*.

In practice, theories of equilibrium, and of complex dynamical systems, offer views of economics which can be complementary. Which is most useful depends upon what we are trying to measure – and more importantly, what question we are trying to answer. Equilibrium theory can offer crucial insights, but our economic systems – the technologies, institutions, physical and social infrastructures on which they rest – evolve. In fact, few if any things in our economies are actually at a sustained equilibrium. And crucially, as Stern notes[160], "The economic response [to climate change] has to be very large, involve dynamic increasing returns, changed economic and urban organisation and design, and the avoidance of potential lock-ins" but "*we have seen models predominate where these elements, the guts of the story, are essentially assumed away*".

Table 1 summarises some of the typical characteristics of complex systems (which largely echo the characteristics observed in our case studies). These elements allow us to identify key properties missing in marginal analysis that matter for analysing large-scale economic change.

Disequilibrium	In dynamical systems theory, equilibrium is a special state, unlikely to last. Persistent and accelerating creation of novelty and increasing product diversity, continuously changing industrial systems and business strategies, are defining characteristics of economic evolution[66], with some parallels to natural systems.[67]
Network effects	A network consists of elements (e.g. financial agents) and connections between those elements. Examples include trading, information transmission, social influence, and lending/borrowing.[68] Their properties depend on their structure and connectivity.[69] Small disturbances in highly connected networks can generate propagating shocks and heavy-tailed risks as well as opportunities.[65]
Diverse interests and expectations of participants	The aspirations and motives of actors in the economy differ – technically, agent behaviours are heterogenous[70] – and cannot always be reliably represented in terms of averages. Agents are not all accurately described as utilitarians[71], while beliefs, morals, aspirations and motives are not cardinally measurable with any certainty.
Emergent properties	In complexity theories, 'emergent properties' are system behaviours that differ qualitatively from the behaviour of individual components. For example, weather phenomena such as hurricanes are qualitatively different from any behaviour of individual water molecules. In the economy, emergent phenomena arise from the interactions between economic agents, and include financial crashes, fashions, the diffusion of innovations and the formation of social groups.
Disproportionality of cause and effect	The frequent existence of reinforcing feedbacks in complex systems creates the possibility, and likelihood, of non-linear change where small input changes can lead to larger than proportional outcomes (the 'butterfly effect'), hysteresis, inertia and additional dynamics.
Path dependence and non-ergodicity	Technically, an 'ergodic system' has the same statistical behaviour averaged over time as over its entire set of possible states, and therefore has no memory of its past. The economy is not ergodic, since the more states the economy explores, the more states it becomes able to explore, which grows faster than the number of possibilities it eliminates.[72] This implies that future scenarios necessarily diverge from one another as small differences in trajectory cumulate over time.[73]
Fundamental uncertainty	The reliability of predictions in complex systems away from stable equilibria generally declines with the length of the projection time span. It may be impossible to enumerate all possible futures with confidence, and "long-heavy-tailed probabilities" frequently arise. Both render the use of statistically expected values unreliable.

Table 1: Key properties of complex economic systems

When the aim of policy is to bring about transformational change, these characteristics of the economy should be central to any analysis. For example, systems that are strongly path-dependent (i.e. strongly influenced by the past) exhibit different behaviour than systems that are not (i.e. in equilibrium). Most systems touching environmental policy are path-dependent: the climate, ecosystems, and the economy. This does not mean that they are unstable; it means that they are built on the past, and the future hinges upon current choices. Actions and choices at each moment in time determine the options that will be available later. Leading economists have identified at least five distinct sources of such path dependencies.[xxxi]

[xxxi] Aghion, Hepburn, and Teytelboym (2019)150 identify at least five determinants of path dependence: 1. Knowledge spillover – a documented tendency for innovations to build upon prior, related innovations in cumulative ways; 2. Network effects – when the attractiveness of a technology depends upon interrelated networks of other users or suppliers; 3. Switching costs – the cost of switching to a different path, e.g. due to the need for different infrastructure and overcome incumbent interests; 4. Positive feedbacks – when technologies benefit from scale; and 5. Complementarities – when technologies have complementary roles, such as renewables and storage.

Equally, when we understand the economy as a complex system, we know that our analysis must consider fundamental uncertainty including the possibility of extreme events. This can be observed in processes of innovation itself[74,75], the diffusion of innovations[52,76–78], and the development of industrial clusters and regional economic development.[79] These are typically self-reinforcing (path-dependent) phenomena, in that the more innovation is made visible/available the more it is adopted, and the more it becomes visible/available. Similarly, the development of new capabilities enables the development of yet more capabilities.

It follows that change in the economy has a direction, a momentum.[80,81] Clearly, it is not the sole result of policy action, but such action can strongly influence both the direction and the rate of change. The economy is in constant movement, and the role of policy is to help re-direct its course towards desired outcomes. Much like the climate system, it sees endogenous change from within, from various currents, turbulence and occasional extreme events.

In practical terms, the implication for policy is that technology choices can have large and long-lasting consequences. In such contexts, it is almost impossible for a policy to be technology-neutral. Any actions will tend to benefit the development and diffusion of some technologies more than others. Over time, the cumulative effect of these choices will determine the shape of the economy and the future pathways it can take.

3.5. Economics of strategic investment and sensitive intervention points

All this points to something very different from a static economic assessment based upon present costs, and the classical policy prescription of 'working up the cost curve' in response to a rising carbon price. For policy assessment, we point in particular to four implications.

The cost-benefit balance of strategic investment and returns

Technologies which are well into the phases of demonstration and market formation may still be much more expensive than the dominant incumbents. Technologies do not magically jump from demonstration to diffusion, and deployment at scale has been essential in bringing down costs of renewables. **Figure 7** sketches conceptually the evolution of costs and benefits (vertical axis) for a new, low-carbon power generation technology. Initially, it may cost several times as much as established technologies, which have benefitted from more than a century of development. Costs come down with learning and economies of scale which accumulate with time and investment. If and as the technology reaches a point of competitiveness, it can start to make a profit against established, fossil fuel-based generators. In addition, the potential value of avoided CO_2 emissions may also be substantial, and should rise over time – but investors are only likely to respond to the environmental cost, and value, if governments put a price on it.

The additional cost of initial deployment applies only for a limited time – and market scale (the third axis) – as illustrated by the initial (light yellow) wedge. As the technology takes off, the benefits may easily outweigh the initial investment costs, amplified by the value of avoided CO_2 emissions, illustrating also how carbon pricing can support low-carbon innovation. The earlier initial investment is made, the sooner the technology costs will come down, and the sooner the cost (and carbon) savings can accrue. In contrast to the common idea that efforts on climate change should increase incrementally over time, the most cost-effective strategy may in fact start high, with innovation and system adjustments then making progress more self-sustaining over time.

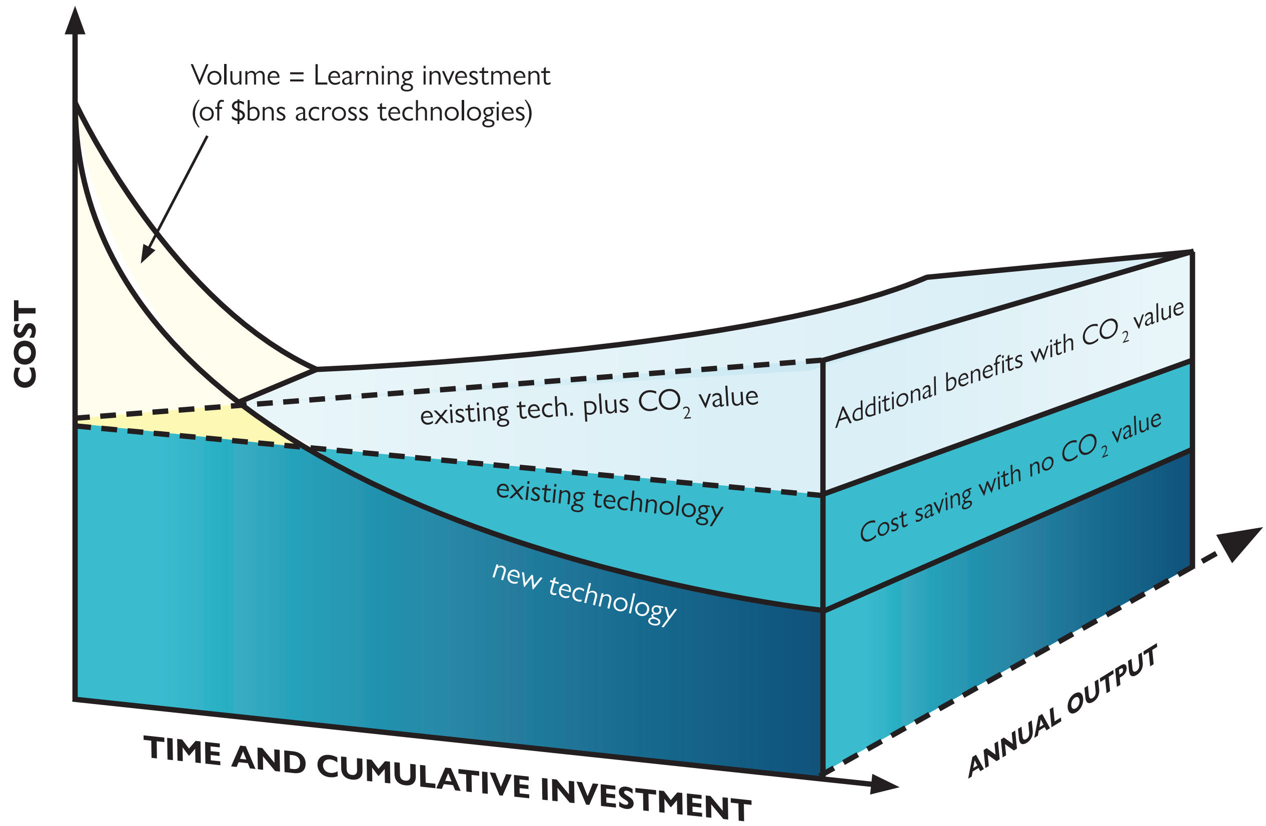


Figure 7: The stylised economics of strategic investment
Source: *Planetary Economics*, Chapter 9, Grubb, Hourcade & Neuhoff (2014).[82]

Technology choice taking account of learning potentials

The history of energy technology investment is not all positive – far from it. Recent research exploring the different patterns (including very different learning rates) suggests at least two key factors which determine the potential for deployment-induced cost reductions. First, technologies that are larger and inherently more **complex** – with many large-scale design elements in the product that interact in multiple ways – learn more slowly, and indeed have more potential for cost overruns. Second, technologies that require extensive **customisation** to local environments, regulatory contents or user preferences, offer less scope for economies of scale in manufacturing and supply chains, compared to plug-and-play technologies. This offers the broad typology, as illustrated in **Figure 8**:

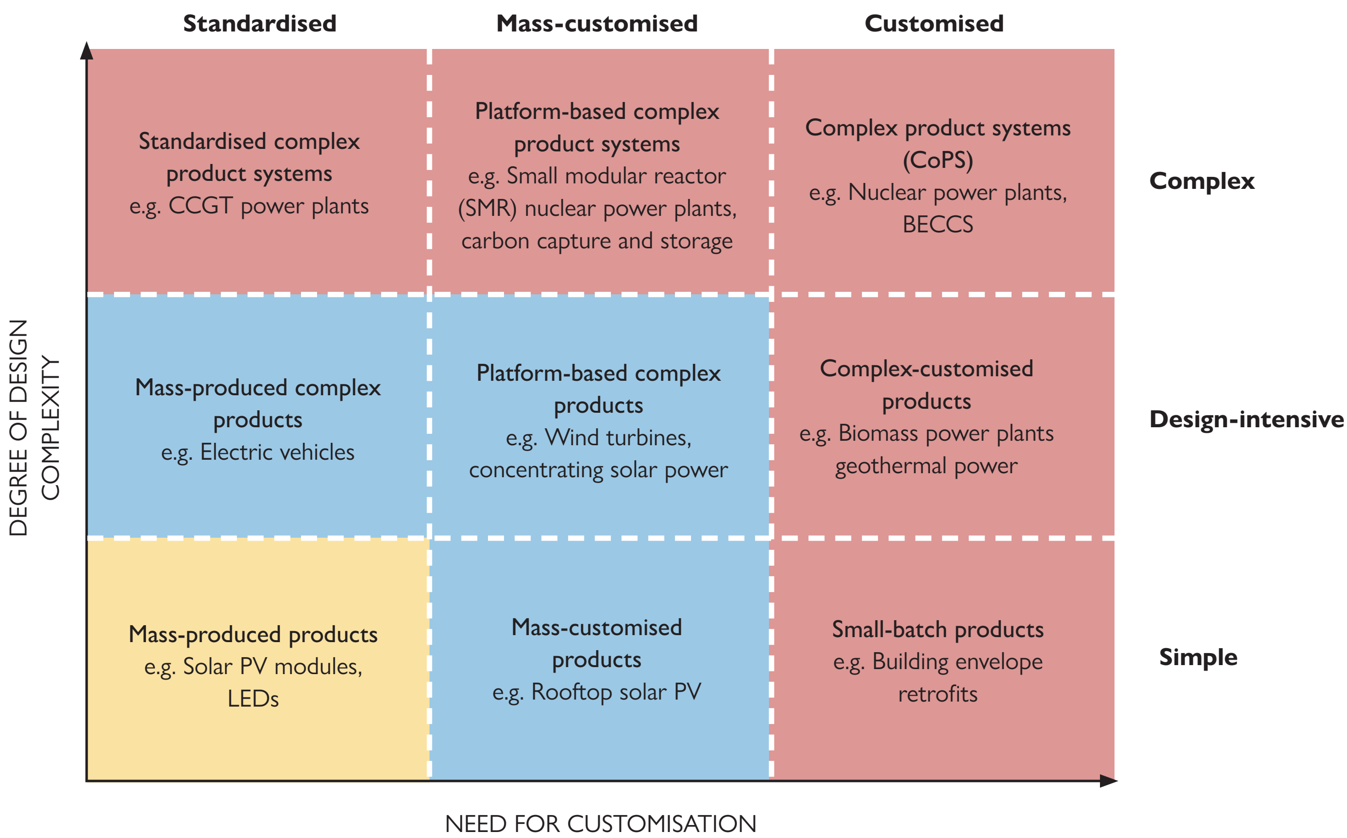
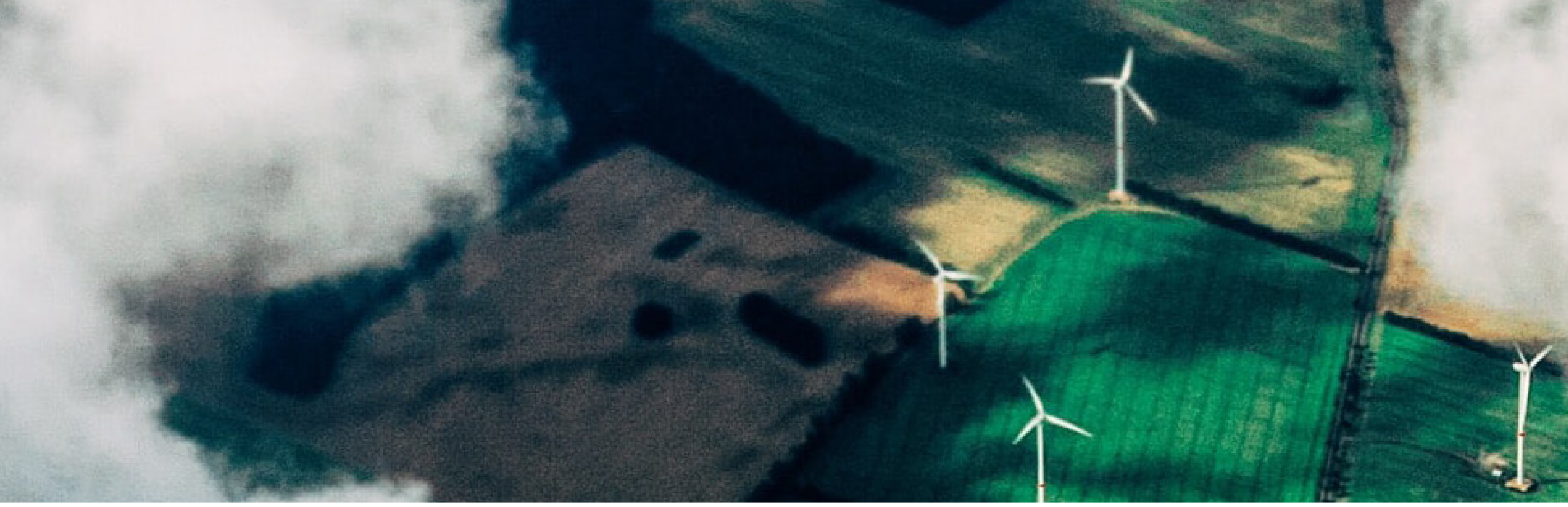


Figure 8: Technology characteristics which influence potential for cost reductions
Note: From Malhotra and Schmidt, 2020[83], who describe these as type 1 (yellow), type 2 (blue) and type 3 (red) technologies respectively (see text).



i. Technologies like solar PV and LEDs which are quite simple to assemble and distribute at massive scale (bottom left) – though they may utilise sophisticated components – exhibit rapid learning and industry-scale economies.

ii. Wind energy involved slower evolution towards standardised designs that could be scaled up, but this did pave the way for offshore – which could hardly be described as inherently simple, but nevertheless embodies standardised components with learning cycles of a few years, increasing replication, and scale economies as deployment has expanded.

iii. Technologies that combine high complexity with the need for extensive customisation (top right of **Figure 8**)[xxxii] – of which nuclear power has become a totemic example – face enhanced risk of cost overruns, with limited scope for rapid learning-by-doing or industry-scale economies.

These three broad typologies, with corresponding expectations for learning rates, also point to different risks, trade-offs and opportunities to be considered in any national investments.[xxxiii, 83]

Historic choices play an important role – for example, the few countries that developed an early wind industry have dominated the manufacture of the most complex, high value components as the industry globalised, while many countries with nascent wind industries compete to develop the least complex, low-value components.[84]

Potential for sensitive intervention points

Within dynamically evolving and path-dependent systems, these are points at which modest interventions could make a large difference – the disproportionality characteristic flagged in **Table 1**. For example, in Germany, the election of the Green Party to the German Parliament in 2000, and its practical and enduring support for renewable energy feed-in-tariffs, has ultimately had huge global consequences. The Brazilian government and BNDES turned a time of crisis in electricity security into an opportunity, which helped not only diversify its own electricity system with wind energy, but also helped given the still-emerging industry global credibility. The progress of lithium-ion batteries for portable electronics[85] created the potential for strides to revolutionise electric vehicles, seized by the US government with a £500m loan that helped to secure Tesla as a viable – and globally market-leading – company.[xxxiv]

Some of these sensitive intervention points may only been seen as such with the benefit of hindsight, or may be unique to their time and location. Others, however, may be more visible and replicable. Targeted subsidies such as FiTs and CfD have proved effective in reducing the cost of renewable electricity in many countries. Tax and subsidy policies that made low-carbon technologies cheaper than high-carbon alternatives have helped the UK and Norway achieve the world's fastest low-carbon transitions in the power sector and road transport, respectively.[86]

[xxxii] 'Complexity' and 'customisation' may be measured in many different ways – see Malhota and Schmidt (2020)[83] for more information.
[xxxiii] The authors characterise these as types 1, 2 and 3 respectively. For type 1, relatively simple and standardised technologies, early investment in R&D and deployment may bring rapid innovation and economies of scale in manufacturing as new knowledge and experience gained in one context (including in the manufacturing process) may be easily applied to another. However, given that production scale is a key determinant of cost – and designs can include technically sophisticated components – production is likely to be centralised. There is potential for 'second-mover' advantage to avoiding early learning costs, but this could involve risks of enduring technology dependency. In principle, high complexity technologies also offer potential for cost reductions, and customisation might enhance potential to capture benefits nationally – but with greater uncertainty and potential risk.
[xxxiv] Note that, in these cases, the sensitive intervention points involved the *fusion* of technological and social factors. The concept of SIPs, with additional actual or potential examples, is explored further in Farmer et al. (2019).[89]

Policy instruments and evolution

Finally, a clear implication is the need for multiple policy instruments – and that the appropriate mix of policy instruments is likely to evolve over the course of a transition. Drawing upon an underlying classification of economic decision-making behaviours into three distinct domains[82,87], **Figure 9** shows how the potential relative significance of the corresponding pillars of policy could evolve. For helping to launch transitions, various instruments of *strategic investment* have generally been needed to move technologies through emergence into rapid growth.

Then as the market moves beyond the emergence phase of innovators and early adopters (**Figure 6**), the structures of markets and pricing become key factors. Pricing to include environmental damages – notably carbon pricing – would help to shift both the direct economics and perceived risks in favour of low-carbon technology, reducing the cost gap to be overcome either through direct public subsidy or private learning investments. This enables the new technology to compete earlier against incumbents, reducing the policy risks associated with, for example, long-term reliance on subsidies. For some technologies, the pace and ultimate extent of adoption may then also be strongly influenced by norms and behaviours, with an important and potentially growing role for policies which address popular concerns and resistance, and thereby encourage adoption at scale.

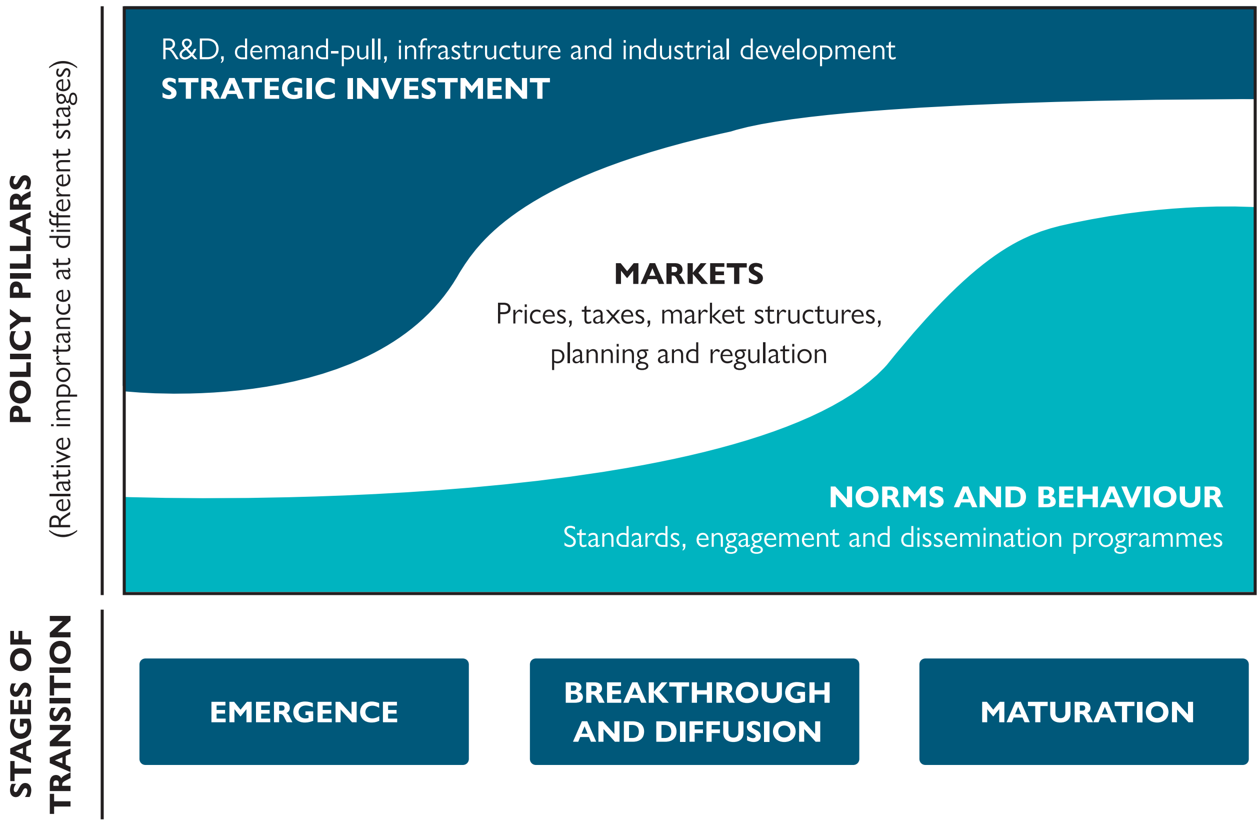


Figure 9: Indicative evolution of policy mix over the course of a transition

4. Deciding how to decide: risk-opportunity analysis

4.1. Introduction to risk-opportunity analysis

In many countries, well-trained public servants are taught the dangers of 'optimism bias', in their own and others' assessments.

This reflects a long history of major publicly supported, or publicly approved, projects turning out to be more difficult and expensive than originally projected, for well-known reasons: in complex projects it is difficult to foresee what can go wrong, but it often does.

Our case studies, however, point to an opposite phenomenon: that of pessimism bias, particularly concerning the potential for technology costs to decline with accumulated experience and the scale of deployment. The essential difference is that cost overruns have tended to occur in relation to ambitious, individually complex and often one-of-a-kind projects. The cost reductions seen in renewable energy and end-use technologies, which are generally less complex and relatively standardised in their design have, in contrast, been associated with rapid innovation in technologies which could be deployed at growing scales with successive rounds of learning and expansion. This corresponds well with both the empirics of learning rates for different technologies, and the typology of different technology types (**Figure 8**).

Governments and modellers have often tended not to consider these dynamics, simply assuming current costs, or simple trend or expert projections. Yet by their nature, the opportunities and benefits of future innovation are less well known than the up-front costs and risks of deploying technologies which are currently less familiar or developed: we can quantify the cost and potential losses of new ventures far more easily than what we may gain from them. Projections for technologies such as solar PV, wind and LED bulbs have consequently reflected the opposite of the traditional problem of mega-projects, of failing to foresee what could go wrong: rather, the risk has been the inability to foresee the improvements associated with industry scale and accumulated experience, given the right incentives and policies.

This is despite the fact that, as charted in the previous section, there is now unambiguous evidence and good theories around the importance of these processes. Such understanding does not, however, offer a crystal ball. As noted, model-based forecasts, such as those drawing on experience curves, do seem to have performed better than simple persistence (current costs) or expert elicitation-based forecasts (e.g. Delphi), but even these serve to articulate important uncertainties – in both levels of investment and associated cost trends – that only grow with the projection horizons. And technology costs are not the only source of uncertainty. A government making policies to start or accelerate a low-carbon transition may hope to attract foreign investment into domestic manufacturing, to create new jobs, and to increase its industries' competitiveness and share of global markets. None of these outcomes can be confidently predicted.

Consequently, one can never precisely quantify the nature and extent or ultimate outcomes of the potential innovation and cost reductions which are inherent in major technological transitions. The use of traditional CBA may give a wholly misplaced and misleading sense of confidence – particularly when individual investments are not understood in the wider context. To assess policies for transformative changes such as those required for deep decarbonisation, we need a bigger toolbox: one that is appropriate for transformational change that moves beyond standard CBA approaches, and that is responsive to dynamic contexts.

[xxxv] In 2010, a UK Government Economic Service (GES) review[151] warned about the limits to CBA in circumstances when policy options have "large, non-marginal or irreversible impacts; on taking social impacts into account more systematically; or on dealing more transparently with the consequences for future generations".[151] The GES review highlighted a number of critical assets and social impacts to be considered in this context. The OECD (2012)[152] *Environmental Outlook* to 2050 detailed similar concerns. Subsequently in the UK, the Treasury led a process to review its guidelines for policy appraisal, provided in the so-called Green Book, which have traditionally been based on the standard market failure framework and CBA as a method, for problems of irreversible transformational change. These resulted amendments to the guidelines, in which 'transformational change' was defined and recognised as a class of challenges for which the standard CBA approaches are potentially inappropriate.[136,153] The new guidelines require impacts in different dimensions to be presented alongside net-present-value estimates, increasing the transparency of decision-making. However, no formal alternate analysis method is yet included in the guidance.

Finance ministries especially may be equally concerned that if policymakers are given free rein to label policies as 'transformational' in intent, and become exempt from CBA, a bias for action may be hard to contain whether or not it is justified. Governments themselves increasingly acknowledge the problem, including in the UK where the analytic challenges around sustainability concerns in general, and climate change in particular, have culminated with significant revisions to the Treasury guidance on policy appraisal, warning about the inadequacies of traditional CBA for these kinds of problems.[xxxv] The challenge remains to define an approach to informing policy under a broad set of conditions that has analytical rigour, demands a proportionate amount of effort, and avoids undue bias in either direction. ROA[xxxvi] seeks to offer an approach.

BOX 6: On costs and benefits, risks and opportunities

Almost all real-world decisions involve some uncertainties in their costs and benefits. Traditional CBA techniques tend to focus attention on average or best-guess estimates. Much of environmental economics, indeed, has focused on how to improve such estimates for environment and resources, and assign values that can be compared with economic criteria.

In reality, these reflect some estimated average across a much wider distribution of possible outcomes, in which different actors have different foci, as reflected in **Figure 10.**

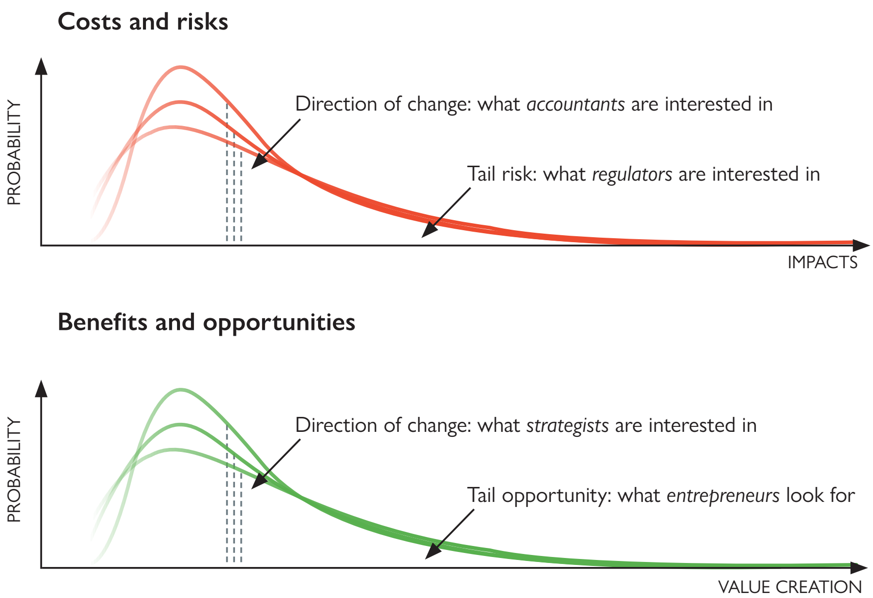


Figure 10: The structure of costs and benefits, risks and opportunities relating to transformational change, highlighting the focus of different stakeholders
The fact that quantities may be characterised by heavy-tailed probabilities implies that high-impact outcomes are challenging to quantify, even when the median outcome is relatively well known (dashed lines). With system evolution, with and without policy intervention, both the median outcomes and the length of the tails may change, for both risks and opportunities, where heavier tail risks imply reduced resilience.

In the context of uncertainty, different policy stakeholders (or policy functions) take different views on what matters. Officers in charge of budgeting ('accountants') are interested in costs, benefits and the likelihood of overruns. Others in charge of strategy ('strategists') are interested in the dynamics of change, their direction, and whether a given course of action can be expected to achieve its goals. The regulation function ('regulators'), such as central banks or market regulation agencies, focus on ensuring that the system remains within acceptable bounds of behaviour, and are thus interested in analysing systemic tail risk – low probability, but highly negative outcomes – and system resilience to unforeseen problems. Lastly, entrepreneurs – whether in public or private sector -, may focus on the development of industry and jobs, with an eye on the tail opportunity – low probability but highly beneficial outcomes – that could contribute to future growth. A framework for the appraisal of policy for transformative change should find a role for all four elements.

[xxxv] *See previous page footnote*

[xxxvi] The formal definition, and a more detailed theoretical discussion, is given in Mercure et al. (2021).[154]

The main features of transformative processes which tend to violate core assumptions of CBA include:

- **Deep uncertainty**[ix]**:** Some or all parameters and possible outcomes are not sufficiently well known to be adequately described with best guesses or quantified probability ranges.

- **Heterogeneity:** The changes involve many actors with diverse interests and concerns, who may be subject to profound rather than modest changes. Consequently, assessment is loaded with issues of social choice and equity not readily subject to 'objective' aggregation. Dimensions can include various aspects that stakeholders may find important (e.g. jobs, income, regional development, health, working conditions).

- **Irreversible change:** Transformative changes typically involve at least some irreversible, 'structural', changes. These could include i) the existence of goods, services, infrastructure, institutions and capabilities, ii) the nature of the relationships between economic variables, iii) the rules and norms of economic behaviour, and iv) the creation of new technologies or resources (e.g. knowledge). Such irreversible change may include 'tipping points'.

In such situations, appraisal should strive to understand the systems involved in terms of dynamic change, acknowledge the diversity of actors and interests, minimise the monetisation of factors that are not primarily economic, and acknowledge knowledge gaps and fundamental uncertainty. Such a framework would inform the four elements of costs, *benefits, systemic risks and opportunities* – but not seek to aggregate them all into a single metric. Some elements of the above are already sometimes considered in policy or regulatory 'policy impact' assessments. One example is that of the UK Energy Regulator Ofgem, which carries a legal duty to protect the interests of both existing and future consumers, and alongside a monetised CBA considers explicitly both distributional impacts, and strategic and sustainability dimensions, of major decisions.

The rationale and role for policy

Because marginal change generally does not create new types of economic resources, the aim is to allocate existing resources as efficiently as possible. From a classical economic perspective, policy action can be justified in terms of correcting a 'failure' and restoring optimality in markets. In situations of non-marginal change, without an equilibrium, an optimal allocation of resources cannot be identified, as the creation of new economic resources and structures is a restless, ongoing process. New opportunities and possibilities are created more quickly than they can be explored.[72] Opportunities are 'endogenous': they may be influenced or indirectly generated by public policies that orient technical change.[88]

Policy appraisal of transformation should then seek to identify possible new types of economic resources and structures, and how they can be most effectively created. In other words, the focus is on *dynamic effectiveness* instead of static *allocative efficiency*: identify where the system is headed and what steer it needs to make progress towards objectives. A 'market shaping' rationale may be appropriate: policy action can be justified if it prepares for change that is likely, brings about change that is desirable, and/or avoids change that is undesirable.[xxxvii] Policy in these conditions is about 'steering' the system through an uncertain, changing environment, in ways that seek to avoid systemic or other unacceptable risks, rather than about 'optimising' an outcome in a static world of assumed certainty.

Key dimensions to inform policy decisions

a) Uncertainty: from costs and benefits to risks and opportunities

Efforts to identify likely, worst and best-case outcomes are important, but the probability and expected value of these cannot be reliably calculated. On the upside, the outcomes most important to policymakers, such as job creation and future industrial competitiveness, may be impossible to predict. On the downside, the potential consequences of extreme events, albeit unlikely, may dominate the analysis – akin to security, rather than optimality. In mathematical terms, (low) probability multiplied by (high) outcome significance yields unhelpfully uncertain numbers. On the upside, the framing is more like enterprise – the pursuit of opportunity – creating options for the economy and business. Underneath metrics of 'average' costs and benefits is a wealth of information pertaining to the transformation

[xxxvii] For example, see the work of Mazzucato[81,155,156] which provides substantial empirical evidence regarding the origins and R&D stories of many widely used technologies that support present-day economic growth. Most of these were created during publicly funded projects until they were taken up by the private sector, thereby shaping markets.

processes involved, new opportunities that may develop and current opportunities that may close, which allow for a much richer basis on which to take policy decisions. The crucial point is that analysis should not be limited to factors that can be quantified. Appraisal should strive to consider all significant opportunities and risks of a policy including the potential for the system to develop in ways that create new options, and the resilience of the system to unforeseen problems.

b) Diversity: from one-dimensional to multi-dimensional assessment

Where there are widely divergent concerns and interests, there is no single, widely accepted method for objectively converting diverse outcome metrics into a single metric – specifically, money. Any approach for valuation – intentionally or not – determines the relative weighting given to different interests and outcomes. Political decisions become at risk of being made implicitly by analysts. Analysts may become risk of politicising their analysis through their choice of valuation methods. It may be preferable to ensure that the weighting of interests and outcomes be made independently by legitimate decision-makers who can be held accountable for their choices or challenged in public debate. To facilitates this, analysis should ideally assess and report to decision-makers the potential risk and opportunity outcomes of policies in all their different dimensions as they are identified, keeping these separate without the need to monetise them into a single metric.

Moreover, monetising metrics obscures the degree to which policies or projects fit within objectives of overarching strategies and programmes, and may in some cases even be detrimental. A key criterion in this case may be whether a policy is consistent with, actively contributes to, or conflicts with, overall strategic objectives. This also involves a criterion of *materiality*. In the case of UK renewables, for example, offshore wind energy is by far the biggest renewable energy resource, which also faced the least political resistance compared to the 'NIMBY' objections to onshore wind. This justifies a legitimately very high premium on policy efforts to foster that technology, and to fund associated offshore transmission infrastructure.

c) Irreversibility: from static to dynamic assessment

Dynamic effectiveness can be assessed by considering a policy's effect on processes of change in the economy. These may include innovation, diffusion, growth, contraction, reorganisation, or replacement of one or more sets of economic resources, assets, or structures, with another. In complex systems, it is typically the relationships between components that determine emergent system behaviour, more than the behaviour of individual components themselves. The effect of a policy cannot be assessed in isolation, but in terms of its relationship to other relevant components of the system.

Reinforcing (positive) feedbacks accelerate change while balancing (negative) feedbacks tend to restrain the system toward the status quo. Positive feedbacks typically produce increasingly amplified effects from an initial disruption, and may lead to irreversible tipping points toward a fundamentally different nature of the overall system.[89] As such, seemingly minor policy action can achieve disproportionately large outcomes if appropriately targeted. The critical difference from traditional analysis is therefore the assessment of policies' potential effects on processes of change in the economy, instead of assessing only their directly expected outcomes.

d) Trade-off between optimality and resilience

It is well known by engineers that highly tuned systems, engines or networks have the potential to fail spectacularly, and that this risk increases the more finely they are tuned. For example, high performance engines fail frequently when run in conditions even marginally outside their optimal range, while lower performance, heavy and robustly-built engines can keep going for decades in all sorts of conditions. Just-in-time supply chains increase distribution efficiency, but also compound the risks of disruption that arise at multiple critical junctions. This is a generalisable principle, where the more specialised an application, organisation, policy or system is, the less it is able to cope with unforeseen circumstances from outside of its usual domain of application. In policymaking, this suggests that efforts to continually 'optimise' the performance of the economy, or a policy programme, could make it less resilient to even minor 'shocks' to the system.

Redundancy is generally the basis of resilience, but it reduces performance under 'ideal' conditions.[xxxviii] For example, adding time buffers in rail network timetables allow train delays to be absorbed and avoids spectacular cascading failures, but makes overall travel times slightly longer. The use of 'stress tests' can help test and estimate the resilience of policies and systems. This is related to what central banks do to test the stability of the financial system to large or small disturbances.[90–92]

From these principles, a framework of ROA can be constructed with the following elements.

[xxxviii] Redundancy refers to multiple system elements with the same purpose or function. For example, engineers typically build redundant power lines in power networks to protect whole networks against the failure of individual lines, notably during storms and other natural events.

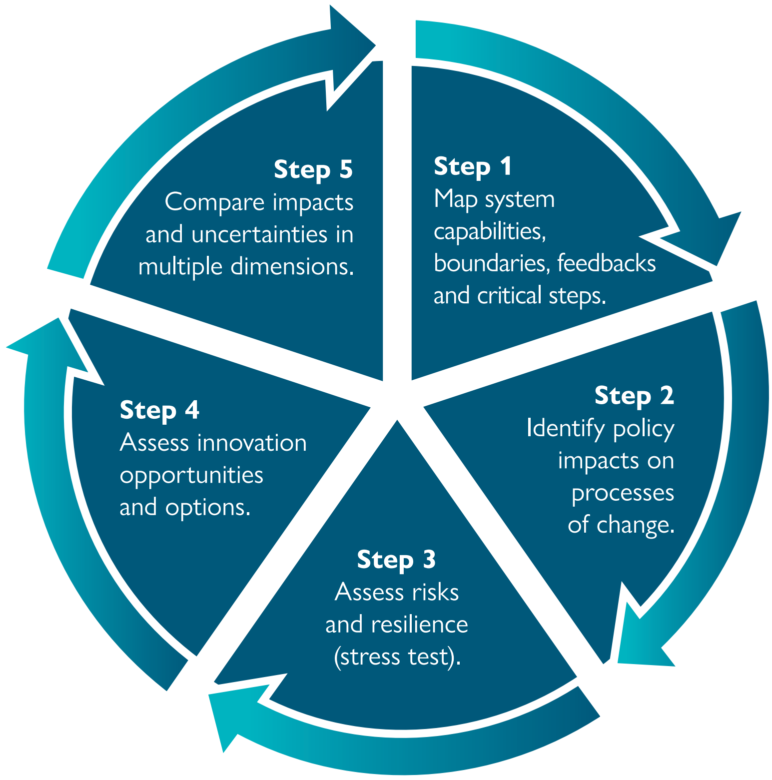


Figure 11: Steps of the risk–opportunity analysis framework

■ **Step 1: Establish objectives, options, key system characteristics and system feedbacks.** Understand the system in question by adopting a sufficiently broad systemic view encompassing the components that matter, and mapping the reinforcing and balancing feedbacks between its components. A model representation (quantitative and/or qualitative) of those systems and their dynamics may help. Identify impact analysis metrics of interest (i.e. different kinds of outcomes that might matter) in consultation with a wide range of stakeholders to ensure suitable breadth, depth and focus in the analysis. Consider the *materiality* of the option being considered for strategic objectives – is it peripheral, or potentially, critical to the overall goal?

■ **Step 2: Identify the impacts of policy options on processes of system change.** This should include consideration of how policy options might strengthen, weaken, create or eliminate reinforcing or balancing feedbacks, and any other ways in which they might change the structure of relationships between components of the system. Likely effects should be compared in terms of direction of change (of any policy variables of interest), magnitude of change (which may or may not be quantifiable), pace of change, and possible accumulation of risk and opportunity (option generation). In this way, the effects of the policy on processes of change as well as estimated outcomes can be considered in relation to all dimensions of interest, and confidence or uncertainty levels or categories assigned to each.

■ **Step 3: Assess risks and resilience.** Drawing upon steps 1 and 2, assess risks associated with the policy compared to the risks it seeks to address. Stress test the resilience of the system and influence of the proposed policies regarding the accumulation of systemic risk, and the likelihood of extreme, if unlikely, circumstances. Probe the most important ways in which the system could fail, and the potential consequences with attention to cascading failures and tipping points, and the existence of low-likelihood, but high-impact outcomes.

■ **Step 4: Assess innovation and opportunity creation.** Carry out an opportunity analysis, to test the ability of the policy to foster 'mission-critical' developments and guide the evolution of the system to a position to capture economic and other opportunities. This includes an analysis of the capabilities that may be developed, the markets that may be created, domestically and abroad. Drawing upon the previous trend of learning rates (section 4.1) and/or the typology of different types of technology with respect to learning potential (**Figure 8**), assess the drivers of and potential for innovation and cost reductions. Large interventions may justify assessing trade impacts, productivity improvements and resources and institutions that may be created.

■ **Step 5: Engage decision-makers on impacts and uncertainties in multiple dimensions.** Impacts, degrees of uncertainty or confidence, and resilience estimates for key metrics adopted in Step 1 viewed together can then inform decisions, with specific reference to strategic goals of the overarching policy and legal frameworks. The preferred option is determined by the decision-maker based on a qualitative judgement of the scale of the opportunities and risks, compared to the cost of the intervention. This will necessarily be a subjective judgement since it incorporates a weighing of outcomes in different dimensions, informed by an objective assessment of likelihood and magnitude of possible outcomes in each of the relevant dimensions. Lastly, capture learning and evaluate the analysis iteratively to determine whether the approach adopted is effective.

Table 2 summarises the key differences between the purpose and rationale for policy action when marginal or non-marginal change is the objective or expectation, along with the appropriate assessment framework, their theoretical underpinnings, and analytical models. In Annex A, we offer a worked example based on a specific historical and influential analysis.

	Where the aim or expectation is **marginal change**	Where the aim or expectation is **non-marginal change**	Reason for difference (in non-marginal case)
Purpose of the policy intervention	Allocative / static efficiency	Dynamic effectiveness	Primary concern is not how efficiently resources are allocated (optimisation), but how effectively economic structures are changed or created (steering)
Rationale for policy	Market failure	Market shaping	Over periods or scales of concern, existing markets are changing, or new ones emerge, so that optimal states cannot be reliably identified
Appropriate analysis	CBA	ROA	Fundamental uncertainty makes precise expected future costs and benefits unknowable
Appropriate models	Equilibrium / optimising	Disequilibrium / simulating	Need to assess effect of policy on processes of change, not just on destination
Theoretical basis	Equilibrium / welfare economics	Complexity economics	Need theory that can explain non-marginal, irreversible and transformational change where relevant

Table 2: Choosing the appropriate set of economic concepts and tools

The challenge of replication and scale

One key limitation to standard CBA that can be inferred from our case studies is that CBA may fail to identify the potential of a sum of multiple policies or projects to collectively and cost-effectively achieve overarching strategic objectives. An analysis of the German solar PV programme shows how the specific investments could be evaluated to take account of the 'learning externalities' based on the observed learning rates.[93] However, CBA may fail by focusing on components which, individually, do not appear to offer value for money, while they do collectively. For example, early offshore wind projects in the UK would without exception have failed a CBA test if on grounds purely of cost-effective emission reduction in the context of near-term emission goals, given the slow initial progress and availability of low-cost alternatives such as carbon offsets. However, the sum of past and present wind projects may now pass the exact same cost benefit test, while in addition offering a wealth of opportunities for future business and employment creation, as a result of the cumulative contribution to learning and supply chain development delivered by each individual project.

Despite this, individual projects or programmes must be assessed, not least because budgets are limited and must be allocated effectively. It remains challenging, therefore, to attribute the contribution of individual projects to the transformational change that they may together trigger, and the likelihood of the this change to actually materialise. Similarly, it remains challenging to identify individual contributions to systemic risk. CBA of a single policy or project should not be considered determinative, if its contribution to the objectives and systemic risk is not sufficiently well understood. One goal of ROA is not to fall in this trap.

A final question concerns whether ROA can guide decision-makers on when to terminate unproductive policies, programmes or projects. Defining 'unproductive' is difficult. For example, temporarily increasing costs in UK offshore wind in the early 2010s could have justified abandoning the technology altogether, preventing or substantially delaying the rapid developments seen just a few years later, and potentially removing what is now seen as a foundational technology for decarbonisation in the UK (and elsewhere, increasingly). Analogies with corporate strategy indicate that a combination of diversity, commitment and a willingness to weed out unproductive ventures leads to the success of companies, while ineffectiveness in any of the three may lead to failure.[94] Governments have deeper pockets, but not infinite resources.

In that context, some elements of an ROA can, at minimum, provide useful clues and options. A visible depletion of innovation opportunities and lack of cost declines could justify termination or scaling back – perhaps with refocusing back on R&D efforts compared to strategic deployment. Conversely, progress in R&D observed in historical data and a visible potential for substantial cost reductions, despite present-day high costs, can justify persistence – as in the case of offshore wind.

Furthermore, an additional opportunity, clear from our case studies, concerns internationalisation. If and when the going gets tough, international collaboration – outlined in our concluding section – may contribute new resources, new skills, and new perspectives and possibilities that maintain and help to globalise progress towards the global goals of decarbonisation.

5. Applications looking forward: electric vehicles and low-carbon steel in China, India and Brazil

In this section, we apply an 'ROA-compatible' model – a 'simulation' model that incorporates insights and mechanisms of innovation, transition and complexity – to two key sectors and technologies for the transition to net-zero emissions: EVs in passenger transport, and clean (hydrogen-based) steel production.

We do so to illustrate how the use of appropriate modelling tools can help guide analysts and decision-makers in the application of a full ROA-based policy appraisal, when transformational change is expected. Further detail on these case studies, and on the model that underpins them, may be found in the appendices.

5.1. Electric vehicles

Road transport is responsible for 48% of global oil consumption, and produces 15% of global CO_2 emissions.[95]

The adoption of EVs is a key part of the solution to decarbonise the sector, particularly for passenger transport.

Technology dynamics. Although the market share of EVs around the world to date remains small compared to ICE vehicles, targeted policies have driven their increasingly rapid growth in key markets globally. Battery costs – a key driver of the cost of EVs – fell 89% between 2010 and 2020[96], through economies of scale and innovation through various forms of learning. Although EVs are typically more expensive to buy, as they are simpler and more efficient than ICEs, they are cheaper to run. In some markets, EVs already offer lower lifetime costs.[97]

Market dynamics. However, driving widespread global adoption of EVs is not straightforward, as infrastructure, supply chains, institutions, incentives, preferences and even the structure of some economies must all be reconfigured to shift away from ICE vehicles and the oil-based products they consume. Although many manufacturers are investing heavily in EV technology as they increasingly see this as the future of the industry, they are also incentivised to maintain the status quo, to avoid the costs of retooling and to maintain returns from decades of innovation and refinement in ICEs. In some countries, this has contributed – along with a perception of low demand – to a constrained supply of EVs. With a limited supply of EVs, few consumers can buy them. They are also unlikely to buy EVs if they remain substantially more expensive than ICEs; however, cost reductions are likely to be driven by economies of scale and various forms of learning as sales increase. Also, companies are unlikely to invest in electric charging infrastructure without sufficient demand to use them, and people are unlikely to buy EVs without sufficient charging infrastructure.

One of the lessons of the case studies discussed in section 3 is that policies are most effective when they directly strengthen the reinforcing feedbacks of technology development and diffusion. Without policy intervention, manufacturers' preference for selling petrol and diesel vehicles acts as balancing feedback, slowing the transition. Regulations that require manufacturers to sell EVs can break this restraining feedback; at the same time, by diverting industry capital into the new technology, they directly strengthen the feedbacks of learning-by-doing and economies of scale that improve its performance and bring down its cost. Consequently, from a simple analysis of the industrial and market dynamics at play, we might expect regulations such as zero-emission vehicle mandates to be highly cost-effective.

Empirical evidence on policies. Prices and standards have both been shown to encourage innovation for more efficient vehicles[24], but EVs represent a radical technological step-change for auto manufacturers and the wider transport system. The evidence is clear that simply correcting market failures, such as pricing the CO_2 emitted from ICE vehicles, is insufficient to overcome the multiple barriers to allowing EVs to become fully established (although once they have been, a focus on adjusting economic incentives can be highly effective in accelerating the nascent transition).[98–100] Limited evidence exists on the effectiveness of ICE vehicle phase-out policies, such as those announced in the UK and EU, however these policies are relatively new and none have yet reached the targeted year.[101] Subsides for the purchase of EVs have had positive effects in many markets by bringing the up-front cost in line with ICEs.[98]

Somewhat analogous to the targets for renewables which helped to drive solar PV and offshore wind developments, EV mandates – which require manufacturers to sell a minimum number of EVs as a proportion of total sales – appear to have been the most effective individual policy where they have been introduced.[102–104] They most directly alleviate the uncertainties facing manufacturers and the chain of supply through to retail, about the scale of the EV market, thus substantially lowering market risks. However, overall, the evidence suggests a combination of policies are required to address different parts of the problem.

Some insights from simulation modelling

Examining the outcome from the use of different combinations of policies on the pace and extent of the transition towards EVs in China, India and Brazil, using a model that incorporates the dynamics of innovation and transition is illustrative (see Online Appendix 4 for details). Maintaining existing policies is likely to see EV deployment sufficient to bring the total cost of buying and running an EV below that of a comparable ICE vehicle between 2028 and 2035 in India and China (**Figure 12**). However, the model illustrates that achieving such cost parity alone is insufficient to drive a rapid transition China, or drive even minimal change in India. In Brazil, cost parity is unlikely to ever be reached, partly due to Brazil's focus on biofuels, effective subsidies on flex-fuel vehicles, the classification of EVs as luxury goods (thereby falling under heavy import taxes), and the very limited number of EV models currently available on the Brazilian market.

Introducing road and vehicle taxes linked to CO_2 emissions, along with subsidies on the purchase of EVs, could help accelerate the transition – but their effect is relatively limited in all countries. The further addition of CO_2 and energy efficiency regulations on new car sales may play an important role in eliminating (particularly high-emitting) ICE vehicles; however, the rate of change increases dramatically when mandates for manufacturers to have EVs as a minimum proportion of their total sales are added to the mix. Thus, the modelling is consistent with observational evidence in suggesting that zero-emission vehicle mandates may be the most effective and efficient policy in accelerating the transition

However, **Figure 12** also illustrates why policies that aim to achieve structural (or non-marginal) change need to be considered together, rather than in isolation, and why the most cost-effective approach may involve a combination of measures. For example, the model simulation suggests that in China, a ZEV mandate alone could achieve cumulative emissions reductions of around 2.5 $GtCO_2$ by 2050. Energy efficiency regulations and a tax on petrol would both have lesser, but still substantial effects. But when the three policies are implemented together, mutually reinforcing dynamics mean the total emission reductions may be around 20% higher than the sum of their individual contributions, reaching nearly 6.2 $GtCO_2$.[105]

Risks and opportunities

Given the huge advances in EV technologies and the rapid development of models by most manufacturers, the technological risks facing EVs are few. Competing against the mature technology of ICEs, EVs are a relatively new technology with far more scope for cost reduction, owing to the intrinsically simpler drive train. Environmental risks are far lower compared to the air pollution challenges of ICEs, and the running costs are much less subject to the vagaries of international oil markets. Taking a multi-pillar approach to drive widespread adoption of EVs thus offers multiple opportunities.

Some of these opportunities are plausibly, approximately, quantifiable. In India, for example, the scale of transition to EVs indicated in **Figure 12** could largely avoid the health impacts associated with traditional vehicles. Moreover at a current price of US$70/barrel, oil imports cost India over $100bn annually. Instead of imports rising potentially to over $200bn/yr during the 2030s, the use of hybrids and EVs could soon cap the growth and lower instead of increasing oil imports during the 2030s.

Harder to quantify – aside from the benefits if e-mobility actually offers cheaper transport – is the potential to share in the development of a new industry, supply chain and expertise for front-runners (potentially with exports), the contributions to emission mitigation, and indirect effects related to strengthened trade balances, currencies and ultimately increase spending on domestic goods and services. EVs may also partially facilitate decarbonisation in other sectors, with their batteries able to draw and feed back electricity to the grid to help balance supply and demand with the increasing dominance of variable renewables.

Many such opportunities in the EV transition are not fully predictable or quantifiable. Appraisal based only on an analysis of quantifiable factors may justify only modest measures to support the transition. This would overlook the potential multiple, more strategic benefits outlined. As explained in our theoretical discussion, the main risks can be readily identified; the opportunities are more unbounded.

Such risks as exist in the EV transition are more to do with the transition away from the existing technologies, and country-specific concerns (including for countries highly reliant on oil extraction, exports and refining).[xxxix] Similarly, countries with large ICE manufacturing industries and extended ICE-specific supply chains may suffer substantial job losses, particularly if they fail to reconfigure towards EVs at a sufficient pace (if at all). The specific balance between such opportunities and risks will vary substantially between countries and over time. However, some of those risks are not necessarily mitigated by avoiding the transition if other major economies embrace it.

[xxxix] Oil markets are global, and therefore declines in oil volumes will be caused by a collective global transition towards EVs rather than from any specific national policies. Therefore risks are collective and not under the control of a particular nation. Hindering the diffusion of EVs nationally to support a domestic oil industry is likely to backfire entirely if several major economies (such as the EU and China) successfully transition towards EVs.

Current policy	What happens?
Vehicle efficiency regulation (CAFC), new-energy vehicle credit programme, direct EV purchase subsidies at national and local levels, (although recently reduced by 20%).	Introducing taxes and subsidies linked to CO_2 emissions could accelerate the already substantial transition to EVs, but to a limited degree. A more wholesale transition to EVs may take place when taxes, subsidies, regulations and EV mandates are combined.
Subsidies for hybrid and EV purchases (FAME), fuel efficiency standards on passenger vehicles.	Introducing taxes and subsidies linked to CO_2 emissions could allow the penetration of EVs, although to a limited degree. The addition of fuel economy regulations may induce a rapid switch to more efficient petrol cars, although an EV mandate is required to facilitate a rapid transition to EVs.
Automakers meeting average vehicle efficiency target qualify for a 30% discount on key taxes.	Introducing taxes and subsidies linked to CO_2 emissions could allow the penetration of EVs, although to a limited degree. The addition of fuel economy regulations may encourage a significant switch to more energy-efficient flex-fuel vehicles. An EV mandate is required to drive the greater penetration of EVs.

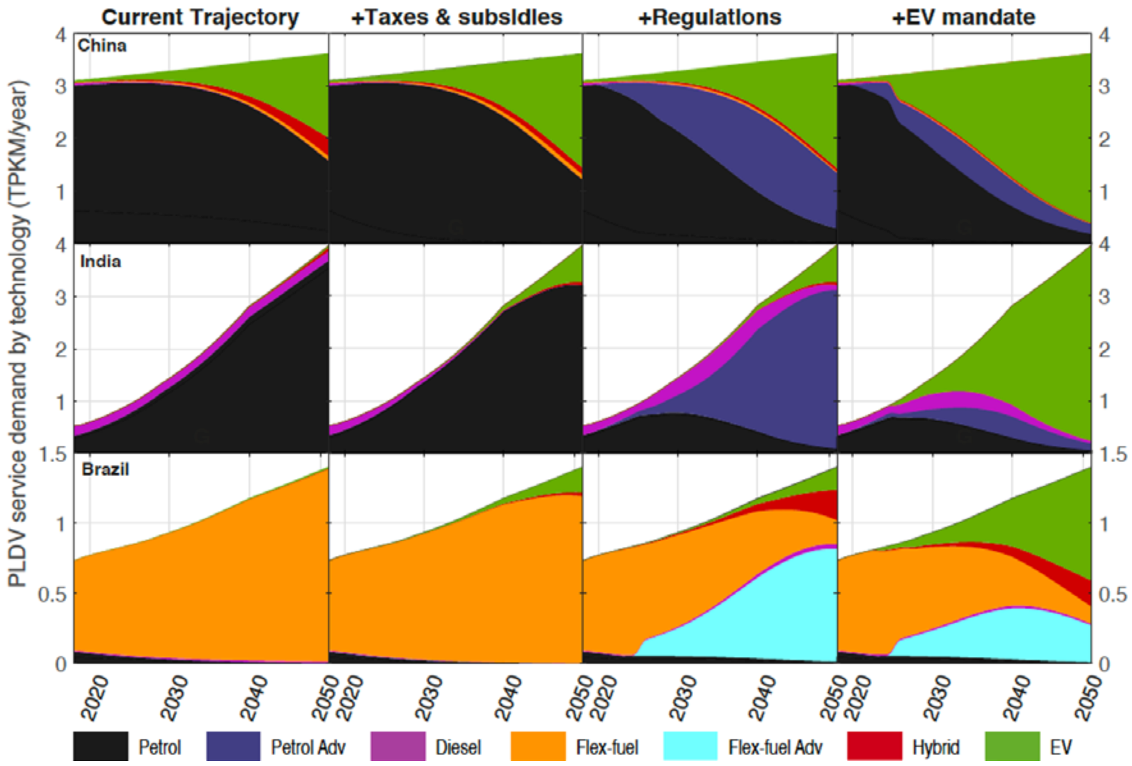


Figure 12: Scenarios for passenger light-duty vehicle (PLDF) fleets in India, China and Brazil up to 2050 under different policy mixes

Note: The Baseline projects current observed trends. PLDV is passenger light-duty vehicle service demand, in terms of distance travelled. Policy instruments include Road Taxes (RT), Vehicle Taxes (VT), Electric Vehicle Subsidies (EVS), fuel economy Regulations (REG), and Electric Vehicle Mandates (EVM). Technologies are divided in three classes of engine power (Economic, mid-range and luxury) and include standard petrol and diesel, a new generation of high efficiency petrol engines (Petrol Adv), Brazilian Flex-Fuel (Flex) and high efficiency Flex-Fuel (Flex Adv), hybrids non-plug-in hybrids (Hybrid), and plug-in hybrid and pure EVs.

5.2. Low-carbon steel

The iron and steel industry, responsible for 7–9% of global GHG emissions[106] and about one third of overall coal consumption, is widely seen as a 'hard-to-abate' sector.[xi]

Beyond primary steel production from iron ore, secondary steel production from recycling generally uses an electric arc furnace with much lower emissions, but this is constrained by the stocks of steel scrap available to recycle, and sometimes contamination. With no obvious materials on offer that could match steel's key properties, significant primary steel production is unavoidable.[107]

Beyond recycling, low-carbon alternatives for primary steel production are limited and mostly experimental. Carbon capture and storage (CCS) is often proposed in order to continue using existing steel production technology.[108,109] For substituting away entirely from carbon-based reducing agents, only two options currently exist: hydrogen-based ore transformation or electrolysis. Electrolysis remains nascent, but hydrogen could play an important role and several steelmakers have announced intentions to follow this pathway.[110]

Steel industries are shaped by domestic primary energy supplies, and thus vary from one region to another. Biomass is used in Brazil as a by-product of liquid bioenergy fuels for vehicles.[111,112] Indian steel production relies heavily on domestic coal supplies and, to cope with low coal quality, steelmakers have used coal gasification to reduce the iron ore, a highly carbon-intensive process. Chinese steel production relies predominantly on blast furnaces. In all three countries, their rapid growth means that most of their historical steel production remains in use, and therefore scrap supplies are small.

Low-carbon steel is by far the least developed of the five technologies we have considered in our case studies. 'Technology-push' policies to encourage experimentation and radical innovation remain highly relevant[113,114] – but with a ferment of activity, attention is shifting to the risks and opportunities of the emergence phase of low-carbon steel.

Steelmaking changes relatively slowly, since the infrastructure and capital required are long-lived (40–60 years) and up-front investments are large. Hurdles in transforming the industry include:

- strong technology lock-ins towards traditional coal-based technologies
- low-carbon alternatives that are largely untested or at a demonstration stage (CCS and hydrogen)
- relatively large capital costs
- the lack of an established market and infrastructure for hydrogen, and its currently high costs.

Positive feedbacks could arise, however, with the development of a hydrogen-based steel industry. Scale and R&D in hydrogen production, as well as hydrogen-based steel technologies, could reduce costs.

[xi] Carbon is the main 'reducing agent' used to chemically convert iron ore, as mined from the ground, into usable metallic iron. This is currently commonly done in a blast furnace, by mixing iron ore with coke (pure carbon derived from coal) and reacting the two at high temperature. This chemical step emits CO_2 and is followed by refining the intermediate product (iron) in a basic oxygen furnace, which uses substantial additional amounts of energy, generally from fossil fuels. The whole standard industrial route (BF-BOF in short) emits on average 1.8 t CO_2 per ton of crude steel production. Other techniques exist to process iron ore; they require natural gas or use coal in a different way, but nevertheless emit CO_2.

Evidence on the impacts of policies

The iron and steel industry has yet to be subjected to stringent policies aimed at decarbonisation. Europe has made the strongest efforts, but the impact of even rapidly rising carbon prices in the EU Emissions Trading System (EU ETS) has been muted, both by the intrinsic difficulty of industrial transition to radically new technologies and the extent of free allowances to incumbent steel producers.[115] Some energy efficiency gains can still be achieved by, for example, reducing the need for precursor treatment of input materials, or by closing old inefficient plants. The Chinese government has mandated the phase-out of smaller, outdated and carbon-intensive facilities.[116] However, the emissions reductions available from further increasing energy efficiency are limited and cannot decarbonise the industry (e.g. Rodrigues da Silva et al. 2018; Pardo and Moya 2013; Worrell et al. 2008[117–119]).

The more radical solutions needed for decarbonisation are only slowly emerging, mostly at experimental and demonstration stages, with the first shipment of 'zero-carbon steel', from a Swedish plant, only occurring in Autumn 2021. There is a rapid growth of demonstration proposals and projects, but steel plants are big and expensive. The risks could be high, but so could the opportunities.

Simulation modelling to provide quantitative insights

Our case study explores the potential of different policy options to guide investment decisions in the steel sector using a mix of technology-push and market-pull policy levers. As with the EV study, we draw upon results from an 'ROA-compatible' model, the E3ME-FTT econometric model, to probe key dynamics (see Online Appendix 5 for details).

Focusing again on the major emerging economies as regions of rapid growth, the model explores the impact of various policy packages on the evolution of the Chinese, Indian and Brazilian steel industries. 'Carrot' policies subsidise up-front investment strategic investment in low-carbon technologies and the use of low-carbon energy inputs, along with a government procurement programme which finances building a nascent hydrogen-based steelmaking capacity. A 'stick' package emphasises market-based incentives such as a tax on CO_2 or carbon-intensive energy inputs.

The cost of hydrogen-based steel depends partly on the cost of hydrogen. **Figure 1** illustrates three policy scenarios assuming roughly the present-day price of hydrogen derived from fossil fuels, around €2,000 /tH_2. For decarbonisation, this assumes that by the time relevant steel technologies are available at scale, hydrogen from zero-carbon sources has declined from recent levels of around €6,000 /tH_2 today) to reach cost parity with hydrogen from fossil fuel sources; see e.g. Newborough and Cooley (2020)[120] for developments that might lead to this earlier than generally assumed. Online Appendix 5 also illustrates scenarios in which hydrogen prices stay high – which impedes transition.

A precondition for clean hydrogen-based steel to become economically competitive is declining green hydrogen prices. Even with this, the model indicates that steel production in all regions is likely to remain dominated by coal if no steel-specific policies are implemented (column 1). China remains dominated by standard blast furnaces, while Indian steel production makes greater use of direct reduction with electric arc, but is still based on coal. Bio-based steel production will likely decline in Brazil, while remaining significant.

Stick policies (column 2) increase the cost of carbon-intensive production and investors look for alternatives. The straightforward alternative is steel recycling, which grows considerably in all the regions. However, scrap resources rapidly become scarce and carbon-intensive intermediate iron products (e.g. from the BF-BOF route) increasingly become incorporated in electric arc systems. Thus, the modelling suggests that with only a carbon price, the steel system becomes trapped in a high-carbon state, while steel becomes expensive.

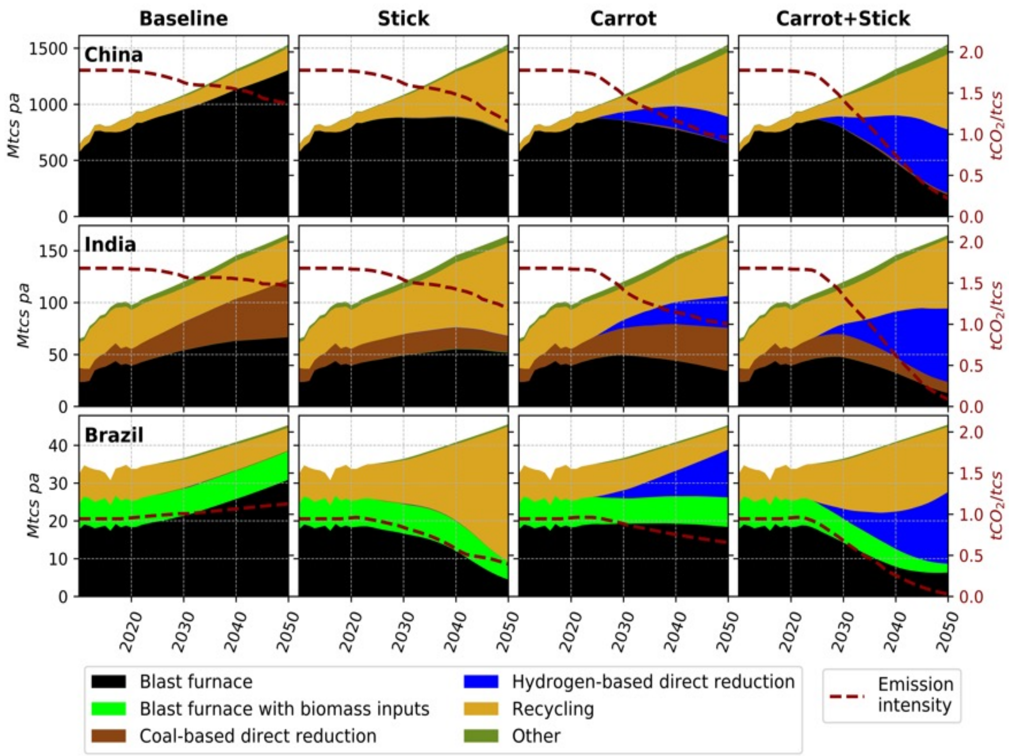
Carrot policies promote a switch towards hydrogen-based steelmaking. Public investment creates a nascent hydrogen-based industry, and the subsidies help replicate it and increase its scale, but not sufficient to substantially reduce coal-based steel (column 3). However combining both stick and carrot packages (column 4) substantially accelerates progress in China and India, with policies reinforcing each other to nearly double the sum of their individual contributions in both countries. A combined push of steel recycling and hydrogen-based steel production decarbonises the system more effectively than other strategies. Success remains highly dependent on future hydrogen prices (Online Appendix 5), which suggests a need for systems thinking in the creation of a hydrogen market, through the aggregation of demand from other industrial users and management of innovation for the producers may be also needed to deliver affordable low-carbon steel.

Current policy

No specific policy is currently in place. Although in March 2020 it was announced that domestic steel production would reduce CO_2 emissions by 30% by 2030 from peak emissions, there are currently no mechanisms in place to achieve this.

No specific policy is currently in place. Coal use is subsidised, although metallurgical coal is largely imported.

No specific policy is currently in place.



What happens?

'Stick' policies drive greater recycling, with modest CO_2 reductions. 'Carrot' policies also induce more recycling, but also leads to some H_2-based direct reduction. Combining 'Stick' and 'Carrot' leads to most scrap being recycled, with CO_2-based reduction largely replaced with H2-based reduction, producing CO_2 savings of over 80% by 2050.

'Stick' policies drive more scrap recycling, in place of CO_2-intenisve coal-based reduction, with CCS increasingly applied to that which remains. 'Carrot' policies encourage H_2-based steelmaking, mostly at the expense of blast furnaces; although coal-based reduction remains cheaper than both. Combining 'Stick' and 'Carrot' policies, tackles this issue, with H_2-reduction and recycling becoming dominant by 2050

'Stick' policies drive recycling of substantial domestic scrap, with substantial CO_2 reductions. 'Carrot' policies induce H_2-based reduction, in place of blast furnaces, with bio-based production and recycling remaining largely stable, with modest CO_2 reductions resulting. Combining approaches induced both increased recycling and H_2-based reduction, leading to very substantial CO_2 reductions.

Figure 13 Scenarios for steel production by technology groups under in China, India and Brazil up to 2050 under different policy mixes

Numbers are in Mega tons of crude steel per annum (Mtcs pa) on the left axis. Average emission intensities of the whole steel sector in each region are depicted by the dashed line and relates to the right axis (in tCO2/tcs). The baseline shows likely projections of technology diffusion if current policies are continued unaltered. The "Stick" scenario shows how diffusion responds to a set of penalising policies (carbon tax and energy tax). The two "Carrot" scenarios show how diffusion responds to subsidies on low-carbon technologies and energy carriers under different hydrogen price assumptions. The latter two columns show projections of diffusion when the "Carrot" and "Stick" policies are combined, for two different hydrogen price assumptions. BF-BOF: Blast furnace coupled with basic oxygen furnace, includes several configurations (such as a CCS variant and top-gas recycling; BF-BOF (bio): A bio-based configuration that has been pulled out of the BF-BOF main group; DR-EAF (gas): gas-based direct reduction coupled with electric arc furnace; DR-EAF (coal): coal-based direct reduction; DR-EAF (H2): hydrogen-based direct reduction; SR-BOF: smelt reduction coupled with basic oxygen furnace; SR-BOF (adv): advanced form of the preceding; Recycling: scrap recycling in electric arc furnace; Other: Remaining technologies.

Risks and opportunities in decarbonising steelmaking

Since low-carbon alternatives are insufficiently proven, steelmakers facing only stick policies most likely continue to use existing technology options, which are limited to steel recycling, subject to supply constraints. In such a scenario, the burden of risk lies mainly with the steelmakers, which likely limits access to finance. Given the higher costs, stick policies would be economically unsustainable without border adjustments. While carrot policies do reduce the burden of financial risk of investing in unproven low-carbon technologies, they do not address the locked-in carbon-based capacity which likely remains dominant due to the incumbent infrastructure in place. In addition, the burden of risk in this case lies solely with governments.

A combination of both sets of policies shares the investment and policy risks, increasing the prospects for private finance at scale. However, supply chains need to be developed. If a low-carbon transition in the steelmaking industry moves towards hydrogen inputs, hydrogen supply needs rapid development. A clear risk arises in leading the industry towards a hydrogen-based future while insufficiently supporting the development of a sustainably priced hydrogen market.

In that lies yet another risk: if hydrogen remains 'grey' or 'blue' (i.e. derived from fossil fuels), the steel industry will reduce its direct emissions while producing steel, but generate significant indirect emissions through the production of this hydrogen. With increasing hydrogen demands, this could potentially lock-in carbon-intensive hydrogen for decades, which would defeat the purpose.

However, potential opportunities arise across the whole value chain and broader industrial system. Significant network effects could occur once the demand for hydrogen increases. As demand grows, scaling and R&D in the hydrogen supply sector are likely to reduce prices which could unlock uses and applications for hydrogen, which could lead to additional demand and further declines in hydrogen prices. For example, hydrogen production can absorb excess electricity production from renewables during moments of oversupply. Hydrogen could become a cost-effective energy carrier for use in other sectors such as long-distance freight transport, shipping, household heating, aviation and the chemical sector, and potentially enable further decarbonisation beyond the iron and steel industry. There are numerous historical precedents for such network effects in industry, including in the origins of steel itself.[66, xli]

The opportunities for low-carbon steel would be enhanced – and the risks of strategic investment correspondingly reduced – if there were clear demand, for example, if EV manufacturers started to demand green steel so as to market their cars as fully zero carbon. This is one route through which the two forward-looking transitions we have considered could, over time, become intertwined.

Conclusions for low-carbon steel

Large-scale decarbonisation of the steel industry seems possible, but only with a stringent policy package that acts to reduce the investment risk for low-carbon alternatives and penalise carbon-intensive capacity to increase opportunities for low-carbon take-up. Neither the stick nor the carrot policies achieve large-scale decarbonisation by themselves, but their combination are likely to induce transformations that reduce emissions significantly. However, complementary policies to develop a sustainable hydrogen sector are also required. The rapid progress in renewables is already starting to create periods with cheap or even free electricity from renewables in some regions, a valuable precursor for green hydrogen, and those periods will grow. An evolutionary, systems view is likely needed in order to coordinate a complex hydrogen transition in the heavy industries.

There is no way that all the costs and benefits of the steps required can be known at present. Low-carbon steel clearly passes the ROA first step of criticality – it is needed – but the system boundaries need to include a view on a countries' potential for low-cost hydrogen (ROA Step 1), and potential demand sectors in infrastructure and transport. The field of options may also be broadened by recognising that steel, ultimately, is a material providing different functions for different uses; innovation in alternate materials could also be relevant. We have indicated briefly the key policies and their likely impacts (ROA Step 2), indicating also that different routes could be appropriate in different regions, based upon local resources and the nature of established industries. From this, we have outlined the potential risks (ROA Step 3) and opportunities (ROA Step 4). In reality of course, these would need to be scrutinised in particular national contexts.

Unquestionably, steel looks like the hardest transition of those we have considered in this report; a final ROA (Step 5) would need to explore options including international collaboration at scale. If there is one thing that our other cases studies have emphasised, however, it is that technology is full of surprises – and that until serious policies start to drive transition, one does not find out. The key to low-carbon steel or other materials does not lie in cost-benefit appraisals that seek to guess the future based on the confines of present knowledge; it requires bold but intelligent assessment of how to maximise the opportunities while minimising the risks.

[xli] During the Industrial Revolution steel became an important material and replaced lower quality iron products once steel became a cost-effective alternative. It became so because the first application of steam engines was to pump water from flooded coal mines. This led to a declining coal price, subsequently inducing a price decline of steel, which prompted a price decline in steam engines in turn, ultimately unlocking its use in transportation, further increasing the demand for steel. Similar – and maybe unforeseeable – dynamics could arise with hydrogen as it gradually replaces coal.

6. Conclusions and implications for international collaboration

This new understanding of the economics of low-carbon innovation and system transitions has important implications for international cooperation on climate change.

With a traditional economic perspective that reducing GHG emissions could only be achieved at a net economic cost (before accounting for the global benefit of avoiding dangerous climate change and before accounting for other benefits related to health and ecosystems), the diplomacy of climate change was seen mainly as problem of burden-sharing – a negative-sum game. Much effort has been spent on the question of how to share this presumed burden between countries. Theoretical solutions may exist[121], but few would dispute that progress has been slower than hoped: global emissions are still rising, albeit more slowly.

It is becoming apparent, however, that we have been "prisoners of the wrong dilemma".[122] We can now see that the original assumption was faulty.

The incentives of various countries to engage in the transition depend on their share of economic risks and opportunities.[123] Zero-emission technologies and systems can be cheaper and perform better than those based on fossil fuels, and can become increasingly so over time. In such cases, low-carbon transitions have the potential to provide net economic gains to societies (even aside from the benefit of avoiding dangerous climate change). This does not make it easy, quick, or even cheap – the renewables revolution has been built on decades of development, and up-front investment totaling probably hundreds of billions of dollars. Yet, it creates the prospect of a positive-sum game: international cooperation that increases the economic benefits to the participating countries (and companies) at the same time as reducing global emissions.

The case studies described in this report illustrate where some of these opportunities for positive-sum cooperation lie. We can group them into a few broad categories[xlii]:

- **Coordinated development and testing of new technologies – to accelerate learning**

In the early stages of technology development, sharing learning between countries and industries can accelerate progress towards identifying viable solutions. Of course, countries and companies like to protect economic value from innovation, and intellectual property remains a thorny and controversial topic. Yet cross-learning and valuable technology spillover was vital in the early development of solar PV and efficient lighting, and conscious coordination even clearer in wind energy – for example the collective efforts of EU countries around the North Sea which included private developers convened by governments through the Offshore Wind Accelerator. The same principle will be equally true in sectors that are now at the earliest stages of their transition, such as steel, and others not directly described in this report, such as agriculture and aviation.

- **Coordinated policies to expand deployment – to increase economies of scale and improve performance**

As zero-emission technologies become more mature, coordinated policy measures can accelerate their spread through global markets, increasing economies of scale and accelerating their cost reduction, as observed in our case studies. Every country that has deployed these technologies has contributed to this progress, making clean power more affordable to other countries. The same dynamic is increasingly visible in road transport and is likely to lead to zero-emission vehicles becoming not just cheaper to run, but also cheaper to buy than petrol and diesel cars (as discussed in section 6). Cooperation can also take the form of practical assistance with the policies that reform markets, mobilise investment and bring down the costs of deployment within a given country.

- **A financial transition**

The practical experience and literatures indicate that finance also is neither perfect nor neutral with respect to technologies. To accelerate global adoption, the terms of low-carbon finance available to developing countries will be important to overcome the 'finance trap' of high interest rates which arises from – but also exacerbates – perceived technological, business and country risk, particularly for newer technologies which do not have established, deep domestic and international financing structures (Ameli et al. 2021). The finance trap has been exacerbated by COVID-19 and escaping it is likely to involve significant transition in financial structures themselves, with combinations of public resources (including through the UNFCCC Green Climate Fund) to leverage private finance into new technology markets globally.[125]

- **Coordinated standards and incentives – to ensure change throughout the whole sector**

Especially in sectors where zero-emission technologies appear likely to be more expensive than fossil fuels for the foreseeable future, coordination on standards could help to overcome the barriers to first deployment created by international competition. This could make it easier for countries to support the kind of policies that may be effective in decarbonising industries such as steel (as discussed in section 6) without having to shoulder potentially high initial investment costs alone (as exemplified by Germany's role in the early promotion of solar PV, described in section 3). This would, in turn, accelerate the global deployment of zero-emission technologies in these sectors and bring their costs down more quickly.

These potential gains are not small. In a recent analysis, the IEA found that without such cooperation, the global transition to net-zero emissions could be delayed by decades.[126] As well as accelerating transitions in each individual sector, international cooperation may be able to activate tipping points that lead to cascades of change across sectors and throughout the global economy, in a manner similar to the large-scale industrial developments of the past.[86]

The distributional questions of climate change are still very real. Just as the dangers of climate change are not evenly spread around the world, neither will the costs and risks of transition fall evenly. Issues of historic responsibility and differing capability for action are no less salient than before. However, the potential for positive-sum cooperation creates a new perspective. Given the evidence laid out in this report, the problem of the global low-carbon transition can be seen as less about burden-sharing and more about the dynamics of investment and returns. This offers routes to minimise the risks – not only of climate change itself, but of capital-asset stranding – and to maximise the opportunities associated with deep decarbonisation. With the climate crisis looming ever more pressing, it is vital to apply the knowledge accumulated through decades of experience with the economics and dynamics of innovation and technological transitions.

[xlii] Following Victor, Geels and Sharpe (2019).[147]

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Annex A:

A worked example comparing CBA and ROA – a historical US energy assessment

The following text is taken from the EEIST working paper 'Deciding how to decide: Risk-opportunity analysis as a generalization of cost-benefit analysis'.[127]

In recent years, many governments have made policy decisions about whether to subsidise low-carbon energy technologies in the power sector, and if so, which of those technologies to support. Cost–benefit analysis (CBA) has often been used to inform these decisions. An example is provided by an influential Brookings Institution study (Frank, 2014[128]) profiled in *The Economist* as demonstrating the economic folly of renewable energy. This study compares the policy options of replacing coal power (the most carbon-intensive technology) with wind, solar, nuclear, hydroelectric and gas power. For each technology, the benefits of avoided emissions are measured using a consistently applied value in dollars-per-tonne of carbon, multiplied by the tonnes of carbon emissions avoided over the course of a year by using this alternative technology, instead of coal. The net cost of deploying each technology as a replacement for coal is estimated by comparing its capital costs and operating costs to those of coal, taking into account differences in capacity factors (the proportion of time that the technology is used to generate power) and differences in their ability to generate power at times when demand is high. The emissions benefits and deployment costs are then added together to produce a single net cost–benefit value for each of the five options. Based on a comparison of these values, the conclusion is reached that the most cost-effective approach to reducing power sector emissions would be to replace coal with gas. Hydroelectric and nuclear power are assessed to be the next best options, far ahead of wind, with solar power being the least cost-effective option of all.

A risk–opportunity analysis (ROA) would have compared these policy options differently.

1. Assessing the potential effects of policy options on processes of change in the economy

In the CBA example described above, policy options are compared on expected outcomes at a moment in time. An ROA would instead compare the effect of policy options on processes of change in the economy.

The processes that lead to changes in relative costs between different technologies would be one component of the analysis. It is well documented that new technologies benefit from reinforcing feedbacks that lead to persistent improvements in performance and reduction in cost over time. These include learning-by-doing, economies of scale and the development of complementary technologies. Observations show that the cost of wind power has fallen by 15%, and that of solar power by 28%, with the doubling of their respective global deployment and that such trends are, in fact, predictable. In contrast, no strong trend is visible over time in the costs of coal or gas resources.

The processes that lead to structural change in the power sector would be another object of analysis. An ROA would consider not only the emissions reductions immediately achieved by each of the policy options (marginal changes), but also the extent to which they create opportunities for further, non-marginal changes. Replacing coal with gas power provides limited opportunity for structural change relevant to the policy objective of reducing emissions. A power system comprised wholly of gas plants would still emit carbon, albeit less than one of coal. If the future policy goal was to continue emissions reductions then these gas plants would eventually have to be replaced, incurring additional costs. In contrast, the diffusion of zero-emission technologies such as solar and wind power, together with complementary technologies such as batteries, increases the likelihood of structural change in the direction of developing a zero-emission power system.

An ROA might conclude that deployment subsidies would be likely to strengthen the reinforcing feedbacks driving cost reduction in wind and solar, but unlikely to lead to the same effect in the case of gas. It could also anticipate those very cost reductions dynamically and assess the likelihood of solar photovoltaics (solar PV) eventually becoming less costly than gas overall. It might assess support for solar and wind as being more likely than support for gas to generate options for structural change relevant to the policy objective of reducing emissions. Finally, it might assess support for solar as being likely to lead to a faster pace of change than support for wind, given the difference in observed rates of cost reduction.

2. Comparing the risks and opportunities of policy options

An ROA would compare the policy options along several different dimensions of interest to policy. These might include:

Cost of electricity: This would consider how each of the options might affect the cost of electricity not just immediately, but also over time, as described above.

System reliability: a rapid transition towards intermittent renewables has system stability implications that are not monetisable but would be assessed, while committing the grid to a gas lock-in also incurs risks that may become challenging to manage at a later stage, which can also be assessed.

Air quality: The burning of fossil fuels, including gas, contributes to air pollution that has damaging effects on public health. Solar PV and wind power do not have this effect, although local pollution can be caused by the mining of materials used in their technologies.

Industrial opportunity and jobs: As solar and wind power take a growing share of the global market for new power capacity additions, jobs in the industries manufacturing, installing and maintaining of these technologies are growing. The same industrial growth is not apparent in the global market for gas power technologies.

International influence: The risk of climate change depends on global emissions, not national emissions. The policy of one country may influence the choices of another, particularly if it is perceived as either notably successful or unsuccessful in meeting its objectives. A government considering support for either renewables or gas may wish to consider how its choice might influence that of other high-emitting economic powers.

Energy security: For countries that are highly dependent on imported fossil fuels, the opportunity to generate power from domestic renewables instead of imported gas might be an important consideration.

Social preference: Some communities may strongly support renewables over gas for the perceived climate change benefits; others may oppose wind turbines on the basis that they spoil the view.

It is up to the decision-maker to determine which of these dimensions are relevant to their policy objectives. For those that are relevant, the task of the analyst is to provide the best available information on the potential effects of policy options.

An ROA would not seek to aggregate the risks and opportunities in each of these dimensions by converting them into a single metric. Such a conversion would necessarily make implicit decisions about the relative importance of outcomes in each of these dimensions. Instead, an ROA would make separate assessments in each of these dimensions, expressing each in its own metric (e.g. dollars per MW hour of electricity, number of early deaths from air pollution, number of new jobs created, proportion of energy imported, etc.) The decision on the relative importance of these diverse interests would then be kept explicit and left in the hands of the decision-maker.

Several of these outcomes are likely to be subject to fundamental uncertainty. For example, the cost trajectory of solar panels may be relatively predictable, but the cost of electricity from a power sector entirely reconfigured around renewables and flexibility technologies is much less certain. The growth of global markets for solar and wind technology may be foreseeable, but the likelihood of a given country succeeding in taking a given share of this market is impossible to quantify reliably. The extent to which one country's actions will influence those of another is deeply uncertain. If the decision-maker determined such outcomes to be relevant to policy objectives, an ROA would not exclude the unquantifiable from consideration; instead, it would provide the best available information on each potential outcome, whether quantifiable or not.

3. Judgement of the scale of opportunities and risks compared to cost of the intervention

The CBA example cited above reaches a firm conclusion: the net benefits of new nuclear, hydro and natural gas combined cycle plants far outweigh the net benefits of new wind or solar plants. Renewable incentives that favour wind and solar are concluded to be a very expensive and inefficient way to reduce carbon dioxide emissions.

An ROA might be more qualified in its conclusions, as it would recognise the inherent subjectivity in the relative weighting given to each potential outcome in their different dimensions. However, it is not difficult to see how an ROA could come to a different conclusion to that of the CBA in this case. On the dimension of electricity costs alone, the ROA might conclude that support for solar power was the most cost-effective option, wind the second and gas the least. This conclusion might be strengthened when the other dimensions were taken into account, given the potential benefits of renewables in terms of air quality, energy supply security and industrial opportunity.

The purpose of this example is not to argue that the CBA conclusion was wrong, and our hypothetical ROA was right. Instead, the purpose is twofold: first, to illustrate how a CBA and an ROA could plausibly reach different conclusions when applied to the same policy decision; and second, to support the contention that the ROA would provide more helpful analysis to the decision-maker in this case. If the decision-maker's interests are limited to short-term marginal change in the power sector, then the CBA may be sufficient. If they encompass non-marginal change in the power sector, as well as outcomes in related policy dimensions – such as industrial opportunity and the effectiveness of the global response to climate change – then the ROA will provide a better quality of analysis.

Case Study Appendices Online
(in separate online documents):

A.1 Wind energy in Europe, Brazil and the UK Offshore
A.2 Solar PV in Germany and China
A.3 The India Efficient Lighting Programme
A.4 Prospects and strategies for electric vehicles
A.5 Prospects and strategies for low-carbon steel

EEIST

Economics of Energy Innovation and System Transition

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